Automating the Force Tactical Picture

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Abstract

This paper reports on research by the UK Defence Evaluation & Research Agency (DERA) into automated compilation of the force-level tactical picture. The necessity for a common tactical picture across a force is discussed and the drivers for improvement in the command's situational awareness are described. The technical design of a Force Data Fusion Technology Demonstrator (FDFTD) currently under development to address these drivers is described. The FDFTD will provide a capability for data fusion to support real-time automated compilation and distribution of the force tactical picture utilising standard tactical data links applicable to single-service and Joint/Coalition operations. Issues encountered in the course of development of the FDFTD such as geo-positional registration, use of tactical data links for data fusion messaging, information management, distributed data fusion techniques, and system architectures are discussed. The experimental programme for the evaluation of the FDFTD is also presented.

1. Tactical Situational Awareness

In order for any group of platforms (e.g. ships, submarines and aircraft) to operate as a cohesive task force, a commonly agreed understanding of the tactical situation is necessary. This allows command and control functions to be exercised in the knowledge that those involved will share a common appreciation of the tactical context and hence are more likely to act appropriately. Without this shared understanding it is highly probable that misinterpretation of the tactical situation will arise, which can lead to incidences of fratricide, avoidable collateral damage or exposure to unnecessary hostile actions.

A force-level tactical picture is a representation of the immediate environment of interest to the command. It assists the operators in forming a mental representation of the world and acting upon it, and guides the command in taking the most appropriate actions. Presently the compilation and maintenance of the force tactical picture require extensive operator supervision and interaction; the command system itself provides only minimal assistance being principally a means of storing and displaying tracks.

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Benefits accruing from the use of multiple sensors covering a wide spectral range dispersed on different platforms in the force have long been recognised. Such benefits are presently realised to a limited extent through the exchange of tracks over tactical data links. The use of data from multiple sensors shared over a data link to form a common tactical picture for the participants of a force can result in improvements to each platform's picture reliability, coverage and robustness, reducing the force's susceptibility to interference or deception. Improved situational awareness arising from greater range, contact discrimination-detection, and sensor data availability superior to that provided by a platform's locally derived tactical picture is therefore feasible.

In addition to the demands for better force-level situational awareness the demands for improved operational effectiveness of individual platforms continue apace owing to:

- increases in target mobility and weapon lethality;
- more complex threats (variety and density of platforms, low observability, countermeasure sophistication);
- greater information loads on operators and the command arising from higher information volumes and rates;
- a new emphasis on operations in the complex and cluttered environment of the littoral.

These necessitate more effective means of integrating sensor data to provide earlier detection times, improved detection-discrimination capability and shorter reaction times.

2. **Data Fusion**

Data fusion is taken to be the process of combining multiple elements of data from a diverse field of sources in order to produce information of tactical value to the user, hence reducing the information load on operators and improving the tactical picture quality. This data, both real-time and non real-time, includes ESM, radar, IFF, infrared, sonar, intelligence information, Operating Procedures and Own Force Plans.

Data fusion usually occurs either at the plot level (i.e. with the raw sensor output, often referred to as measurements) or at the track level (i.e. after a track extraction state estimation process). Different sensor types produce different types of data, for example range/rate for radar, bearing for ESM and acoustic signature for sonar.

Data fusion can be classified into three levels [Waltz & Llinas, 1990]. Level one is the data fusion subsystem, levels two and three form the decision support system involving situation assessment and threat assessment respectively.

Detections and tracks are obtained by different sensors, these sensors have different geometries so the information from these sensors must be converted to a common spatial and temporal reference. Assignments may be formed to existing contacts that also allow tracking information to be updated, which improves the estimate of the contact's behaviour.

A function then combines sensor data association with each contact to categorise into class, thereby giving the identity. Many categories of stored information may be used to classify contacts, such as structural models to define the relationship between measured contact attributes (acoustic/radar signatures, radio frequency emissions, etc) and contact classes, and behavioural models to relate the temporal behaviour (velocity, altitude, etc) and spatial behaviour (contact formations, weapons ranges) to contacts and events.

After level 1 processing the following types of information are available:

- location of contacts and events;
- estimated dynamic state of contacts from which future behaviour can be predicted;
- identification of contacts and associated uncertainty or ambiguity between multiple possible contacts;
- situations of military importance resulting from individual contact locations, behaviour or aggregate behaviour of multiple contacts;
- sensor allocation assignments, schedules or priorities for each contact.

3. **System Rationale**

The use of knowledge-based systems for picture compilation, situation assessment and resource allocation has been researched in DERA over the last ten years. An important product of this research is the Combat Management Integration Support Environment (CMISE) which forms the test-bed for investigation into new and improved techniques for Combat Management Systems. CMISE is a real-time, multi-user system using a generic rule-based approach to data fusion with interfaces to operational systems enabling operation both in the laboratory and in the field. Following five years of trials at sea, functionality developed in CMISE is being integrated with the RN command system, ADAWS, aboard HMS Ocean and will provide the picture fusion capability for the Replacement Maritime Patrol Aircraft, NIMROD Mk 4. CMISE continues to evolve with the research programme and is currently being enhanced to form the Force Data Fusion Technology Demonstrator (FDFTD).

CMISE was developed as a number of loosely coupled modules (described below) supporting particular functional groupings essential to a combat management system, namely; picture compilation, situation assessment and resource allocation. These modules are integrated through a software layer providing common services and interface to the rest of the platform systems via a gateway onto a Combat System Highway (CSH).

In addition, a server module provides a common set of access functions for the user consoles and additional applications requiring data stored and produced within the system. The logical architecture of CMISE is shown in Figure 1 below. The system was originally implemented on a collection of computer workstations connected over Ethernet. However, with the significant advance of processing power, it was possible to co-locate the software on a single Digital Alpha workstation, with user interfaces running over X-windows on networked terminals.

The Data Fusion Module (DFM) provides automated functions for compiling a tactical picture. It performs the data fusion process by correlating data from all available sources (on-line sensor systems or manually input plans and reports). In addition it combines evidence to determine platform position, velocity and identity parameters.

The Situation Assessment Module (SAM) provides facilities associated with force-wide tactical assessment based on the results of data fusion. In association with the data fusion module, it provides automated functions for compiling a tactical picture. It is also responsible for providing a set of facilities for assessing the tactical picture and producing a more concise situation display, to capture the groupings of platforms, including their roles, inter-relationships and capabilities. This module is also responsible for the production and maintenance of threat tables and keeping track of own-force resources.

The Resource Allocation Module (RAM) covers the following areas at force and ship level: analysis of feasible soft and hardkill actions, optimisation of engagement, conflict resolution, application of doctrine, and manual interaction.

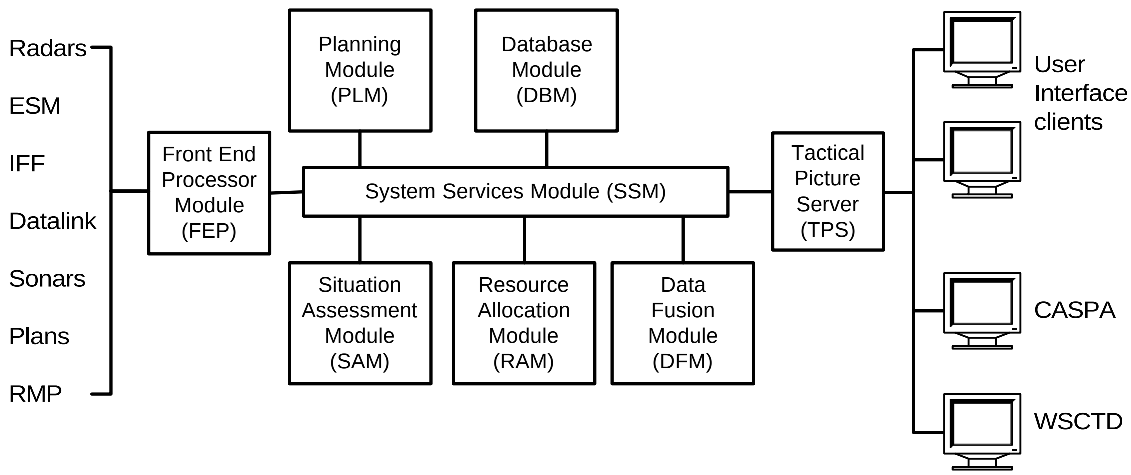

Figure 1: CMISE Logical Architecture

The Database Module (DBM) provides a means of storing and accessing fixed or infrequently updated data, i.e. geographic, platform and equipment data, plus some mission data such as IFF identity codes.

The Tactical Picture Server (TPS) enables the user to interact with CMISE including the display of spatial pictures produced at each level of reasoning within data fusion and situation assessment, requested data on specific objects and explanations of the reasoning process undertaken by the knowledge based modules. TPS also provides access to the databases and local functions for display configuration and tactical calculations, and allows other applications such as Planning Aids (CASPA) and Weapon System Co-ordination (WSCTD) to interoperate with CMISE functionality.

The Planning Module (PLM) manages plan data within CMISE, entered in signal format via the TPS, providing validation and translation functions to prepare the plans for processing by DFM.

The System Support Module (SSM) provides the operating environment for the application modules of CMISE, and offers facilities to support loading and controlling CMISE operation, management and propagation of fault information, management of inter-module communication and system-wide facilities such as the system clock. All other modules incorporate parts of SSM to provide these features.

Finally, the Front End Processor (FEP) provides the link between CMISE and the platform's equipment interfaces via a network such as the Combat System Highway (CSH) on many RN ships. An extensive simulation facility, OOPSDG, also provides detailed simulation of sensors, networks, interfaces, contacts and the environment to support the development and testing of CMISE.

3.1 *CMISE Data Fusion*

The structure currently used in CMISE for data fusion is implemented using a rule-based system of the general type: (if << condition >> then << action >>).

Rules are grouped into 'knowledge sources' acting via a scheduler on a 'blackboard structure' containing 'hypotheses' (linked data structures containing input or derived data). The 'blackboard' uses three levels of hypotheses of increasing abstraction and consists of:

- the input data, either tracks or reports;
- correlated tracks, which are called multi-tracks;
- vehicles, representing real world objects.

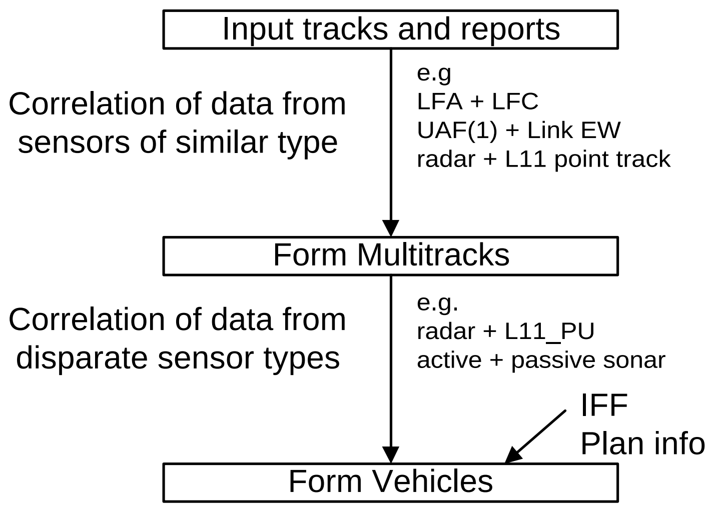

Figure 2: CMISE Data Fusion Process

The DFM implements data fusion in a three-tier hierarchy as shown in Figure 2. Track objects are correlated to form multi-track objects, which are then correlated to form vehicle objects. Earlier work [Miles] defined the concept of different levels of data fusion and how a hypothesis at one level can 'support' those at a higher level and be 'supported' by those at a lower level. For example, consider multi-tracks, these support vehicles and are supported by tracks; in the case of sensor status, these will support the hypothesis for the platform on which the sensor is located.

Vehicle attributes include (but are not limited to) position, standard identity, environment, platform type and class/name:

- standard identities are friend, assumed friend, pending, neutral, unknown, suspect and hostile;
- environment attributes are air, surface, sub-surface, land, space and unknown;
- platform type can be bomber, interceptor, destroyer, frigate, missile, etc;
- class/name attribute can be Type 23, Sea Harrier or a name such as HMS Invincible.

The actual vehicle identity will be one or more of these attributes; which one is determined by the quality and amount of data from the sensors.

A new track always forms a new multi-track and (tentative) vehicle (V'). The track is then compared against other vehicles' tracks and multi-tracks in an attempt to correlate it, if the correlation is possible a tentative link is established between the new track and the associated multi-track. New track updates either confirm correlation or the correlation fails. A track can have tentative links with more than one multi-track. A correlation link will confirm when only one link remains. If there are no tentative correlations the track is classified as an established vehicle (V). Figure 3 shows this process.

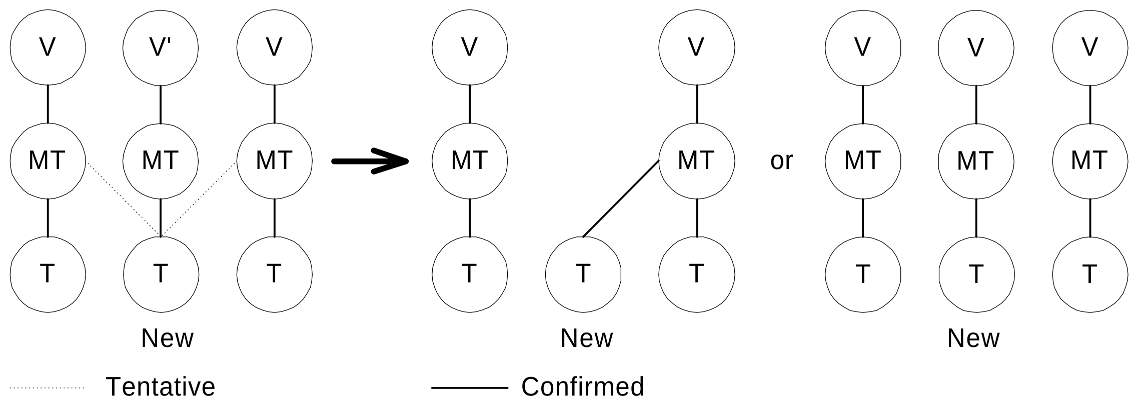

Figure 3: Track Correlation

Other, more involved, processes also exist to cover multi-track repair, correlation, track confirmation and inclusion of collateral data (e.g. plans, IFF).

4. Force Data Fusion Technology Demonstrator

The Force Data Fusion Technology Demonstrator is a DERA project – under sponsorship of the Royal Navy's requirements branch, EC(AWB) – that is investigating the automation of the force-level tactical picture compilation process by the creation of a representative testbed system.

The mission of the research is to demonstrate two or more platforms each with high levels of automated data fusion communicating and co-operating in the generation of a force tactical picture using machine-assisted picture compilation techniques.

The representative testbed that the FDFTD provides will enable:

- effective techniques for force-level data fusion to be identified;
- the feasibility of distributed data fusion to be demonstrated;
- conceptual foundations of distributed data fusion to be established;
- further applied research into distributed data fusion to be pursued;
- achievable performance of force-level data fusion to be quantified and compared with current and proposed systems.

Automation of the force tactical picture compilation process using rule-based data fusion techniques can confer a number of advantages on platform and force capabilities. These arise from an increase in the knowledge that the computer system has about the environment allowing more informed decisions to be made about what constitutes useful data to exchange and enabling additional information to be inferred to form a more coherent and complete tactical picture.

The objective of adding automation should be to create a synergistic partnership between man and machine that will produce the optimum solution with the data available, i.e. the machine undertaking the mundane, repetitive and time critical processing allowing the human to concentrate on the higher level issues that are more suited to the flexibility of the human mind.

The Force Data Fusion Technology Demonstrator, an evolution of CMISE, provides a force level tactical picture compilation capability over the standard data link, JTIDS/Link 16, and is compliant with STANAG 5516. The FDFTD uses a rule-based data fusion approach to compile a platform's tactical picture from its own sensors (radar, ESM, sonar and electro-optics) and the data available over the tactical data link from the rest of the force, and automates the release of tracks onto the data links. Functionality has been developed that enables the fusion of local with data link data to be achieved reliably, and to allow fused data to be released onto the data link without causing problems of data incest or knowledge reinforcement. The use of JTIDS/Link 16 ensures interoperability with non-data fusion systems minimising costs and re-engineering. The FDFTD consists of five major elements:

- the data fusion engine;
- control processes and logic to manage the reception and transmission of data link messages;
- position enhancement functionality that improves the localisation of contacts through the calculation of the intersection of sensor error ellipses;
- conflict resolution functions to manage the differences in the platforms' tactical pictures across the force to ensure that a common force-level tactical picture is maintained.
- information management functions to optimise the quality of the force tactical picture by managing the type and frequency of messages sent over the data link;

The FDFTD has been developed as part of a three-year programme of research, and has recently started its final year of development. The FDFTD has already achieved the reliable transmission and reception of Link 16 messages and the fusion of radar tracks from Own Unit and the data link using a laboratory-based synthetic environment. The position enhancement functionality has been prototyped and shown to have the potential for significant improvement in contact localisation by providing local-local and local-remote position enhancement. Support for exchange and fusion of Electronic Support Measures (ESM) data into the force picture is currently being developed, with the intention to include other sensors such as sonar and Electro-Optic (EO) in later versions of the FDFTD.

4.1 *Registration*

The specific information required within a force will depend on the specific tasks of each Unit; however, the two essential items of information that must be held in common are position and time. Each Unit must know 'where' it is in relation to other Units (friendly, neutral and hostile) in order to co-ordinate movement, search, attack and defence. Object positions may be relative (referred to Own Unit/force) or absolute (referred to a fixed point on the earth's surface). A common spatial reference is essential for all these processes in order to allow external track reports to be fused with organic (Own Unit) tracks.

Accurate geopositional registration of sensor reports and tracks is imperative if automated data fusion is to be achievable. The concepts of geopositional referencing as used in Combat Systems has been reviewed [Davison1], and appropriate recommendations were made for further work in support of CMISE. This was extended by an investigation [Davison2] of CMISE areas that are dependent upon the georeferencing co-ordinate system, and explored possible improvements in force data fusion by better geopositional representation in naval systems, and those areas of CMISE that would be affected by adopting an earth-centred co-ordinate system.

The impact on the hypotheses, rules and operations within CMISE that would be affected by a change to an Earth-Centred Earth-Fixed (ECEF) model was investigated. The conclusion was that for force data fusion an ECEF model is not necessary, as the increase in accuracy would have little bearing on data fusion so long as the tracks passed are referenced to a suitable earth model such as WGS84, which is provided by the JTIDS/Link 16 data link system. Therefore only minimal changes were necessary for the FDFTD.

The positional accuracy of tracks reported over data links is expressed as a Track Quality (TQ) value in the link messages. The TQ is derived according to the size of the area in which there is a 0.95 probability of the contact being located. The higher the TQ value the smaller the area of uncertainty. The precise TQ to uncertainty area mapping is classified and specified in the relevant STANAG. TQ computation is required to take account of the:

- design accuracy of the sensor that generated the report;
- elapsed time since the last sensor update;
- most recently calculated velocity of the track;
- Own Unit’s current geodetic position quality.

All Units must share a common appreciation of time in order to know ‘when’ to synchronise movements, responses and reports. Information from multiple sources will be generated at different times. All of this information must be normalised (e.g. interpolate tracks) to the same time reference to make satisfactory correlation possible. The staler a piece of information is, the less likely that it will be able to be accurately incorporated into the picture. JTIDS provides highly accurate temporal registration based on internal chronometers and Time of Arrival calculations. DLPS acts as the host processor for JTIDS/Link 16 and hence dead reckons tracks before transmission modifying the TQ of transmitted tracks.

4.2 *Data Link Track Management*

Whilst having more data available from which to deduce objects helps improve the quality of tactical information for the Command, too much data can reduce the accuracy and clarity of the information. There is therefore some limit at which point additional data provides no extra *knowledge* about an object and may even increase the uncertainties with the data already held. The ‘worth’ of the data must therefore be assessed before it is contributed to the force tactical picture. The fusion process should therefore exhibit some ‘intelligence’ in the selection and use of the data available to it from the Units of the force. Although informed estimates of the limit can be made at this stage, one of the purposes of the research is to investigate the optimum combinations of data for the best quality picture.

A combination of Reporting Responsibility (R^2) and TQ is used by the current data links to maintain tactical picture quality (by limiting ambiguities) and limit the load on the data links. A measure of track quality is used to establish which Unit is the most suitable to report the track. The Unit then assumes R^2 until such time that another Unit has a sufficiently higher TQ to take over the responsibility for reporting the track.

Correlation of local with remote tracks received over the data links is used to indicate which reports are to be dropped from the links so that only a single report remains. This restriction maximises the use of the (limited) data link capacity and eliminates the 'confusion' that multiple track reports can cause to current command systems, which do not have platform-level automated data fusion and hence cannot cope with multiple reports on the same contact.

These are, however, coarse mechanisms for achieving this and require operator supervision. R^2 is essentially a precedence based mechanism that naturally precludes collaboration in building a force tactical picture by preventing multiple reports on a single contact. It has the disadvantaged of reducing the diversity of the source data; the R^2 rules do not allow for redundant reporting of contacts which are useful in many situations, e.g. resolving ambiguities such as converging then diverging aircraft, i.e. track bounce.

One of the major concerns when autonomous Units share data is data incest. This arises when data passed on to another Unit is subsequently fused with other data, which is then passed to the original Unit. To avoid this, the data needs to be partitioned or tagged with the source (the reporting Unit and sensor) and not retransmitted by the receiving Unit.

Information management requirements have been investigated with the aim of improving the utilisation of the constrained data links capacity. The FDFTD will make use of the standard data link functions for controlling message reporting and frequency, not only to automate the management of the tactical picture data, but also to allow link capacity to be made available for additional reports to support position enhancement.

4.3 *Position Enhancement*

The data link R^2 rules permit only the Unit with the best quality position data to report a surveillance track on the link. This strategy prevents other tracks from contributing additional information to produce a more complete combined force opinion. The FDFTD extends the data link protocols to allow multiple Units to concurrently report position information for separate sensor tracks on a single object (as judged by the track association carried out in DFM). This additional information is combined by FDFTD Units to produce a (potentially) more accurate position estimate for Real World Objects (RWO) through the intersection of sensor Area of Uncertainties (AOU).

Information from sensors producing similar types of information may be fused to achieve reduction in uncertainties. The benefit of multiple ESM and sonar *bearing* reports is based on the considerable decrease in area of the uncertainty region and is implemented within the current data link systems (i.e. Link 11 and Link 16). The benefit of multiple *point* reports, e.g. radar derived reports, is not as dramatic. Current data links (based on earlier designs) have not seen the benefits outweighing the costs, and so such functionality has not been implemented. However, in a more demanding environment and with greater capacity and processing power available, the benefits are both more important and cheaper to implement. These benefits include:

- the resultant composite track formed from the multiple reports has a higher sampling rate, (providing more accurate and robust tracking, more robust correlation, and better responsiveness to manoeuvres);
- multiple reports can assist in the resolving of correlation errors arising from the application of reporting responsibility rules, e.g. in the case of track bounce;
- reduction in composite track AOU from the overlap of sensor beam error regions;
- provision of height information on a contact when reports are available from at least three Units.

Position enhancement processes the areas of uncertainty from multiple correlated tracks to obtain an intersection region. The uncertainty regions are dead-reckoned using the velocity data taking account of the uncertainty in velocity to expand the position AOU. Both point and bearing tracks are used. Figure 4 illustrates the incorporation of a single data link track in two dimensions.

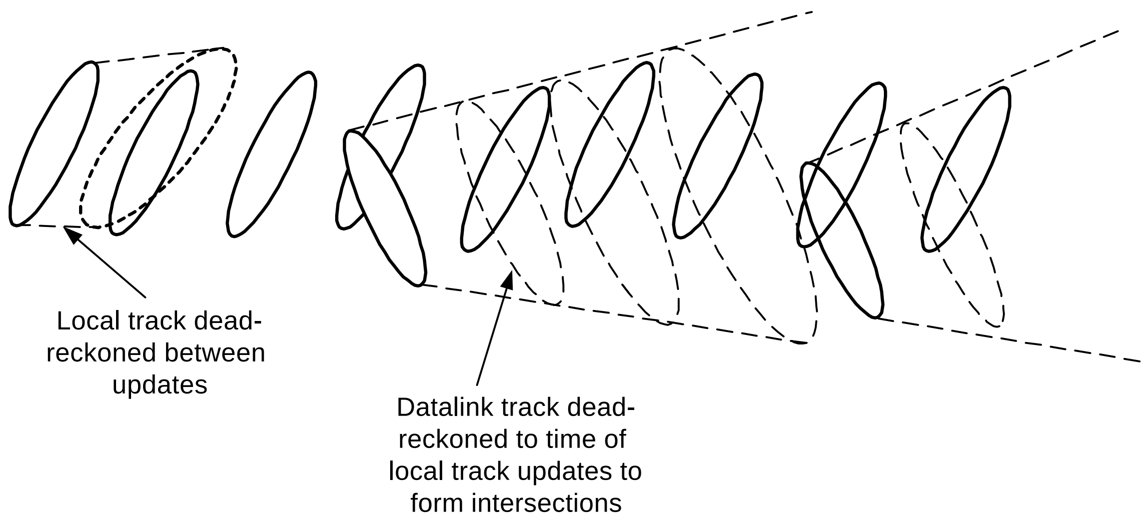

Figure 4: Local-Remote Track Intersection

Multiple data link tracks, and for that matter multiple local tracks, can provide more significant improvements in track quality. While local-local fusion of point tracks provides a much smaller improvement in AOU, it is more efficient to broadcast a single local track per platform per real world object. The fusion rule of earlier versions used the track with the best position quality, which was therefore consistent with the data link best contributor R^2 rule. In order to maintain consistency with the new link fusion rule, the local tracks are combined using the same method and the resulting intersection sent.

Considering the track quality as a function of time (Figure 5 below), it is possible to see how this approach improves the overall quality of the force picture. Track A updates have the single highest quality, and under the current data link method only this track would be reported. Track B has a lower quality, and indeed a lower update rate, but its quality decays more slowly because the radar is providing much more accurate velocity information. Therefore, for most of the time track B is better than track A. In principal, the R^2 could pass between these two tracks, but on many occasions the changeover does not occur at the time of an update, but as a result of dead reckoning error expansion. For practical efficiency reasons, data links impose hysteresis to prevent frequent R^2 switches.

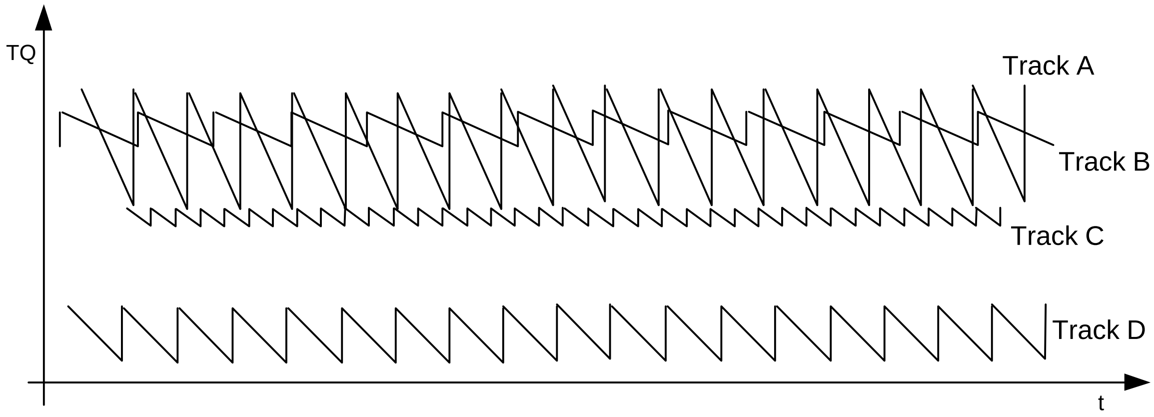

Figure 5: Variation of Track Quality for Common Contact

Track C has a high update rate and consistent quality. Although taking track C alone gives no improvement, the fusion of tracks A, B and C will have a higher quality than that of A and B alone.

Although track D has a low quality, the sensor it represents is distant from the others. With the long baseline, the improvement gained by incorporating its data is out of proportion to its apparent low quality. The combination is greater than the sum (or even the maximum) of its parts.

Many standard surveillance radars provide no precise height information, or even any indication of the estimated height range. Contact positions are measured in spherical polar format (slant range and azimuth only; elevation omitted) by the radar, converted to Cartesian format (X and Y co-ordinates) by the associated tracker, and provided to the Combat System. This Cartesian format data is supposed to be the projection of the position onto the plane tangent to the Earth at the radar position, but the lack of elevation measurement suggests that the slant range is incorrectly used as the ground-plane range in this calculation. This causes a small dilemma: should the data fusion assume the data is what it is meant to be, or take account of the likely error introduced by an incorrect implementation? In the hopes of the implementation being corrected, force data fusion assumes that the information is as specified when height is available, but is slant range when there is no height. The situation with height included is complicated, and has not yet been fully implemented in CMISE.

The concurrent reporting of a common surveillance track by more than one Unit would violate the reporting rules defined in the data link STANAG. The allocation and use of a different Force Track Number by another Unit to report a common RWO on a data link would confuse the picture, and lead to additional operator involvement to resolve the correlations that will invariably be made. Hence it was not practical to consider use of the existing link messages to concurrently report tracks without them being modified to indicate their use in this mode, and the interpretation of this information by all the data link participants. A method has therefore been derived to allow FDFTD Units to report privately over the data links their contacts on common force objects, which are then used to enhance the position of the track reported on the surveillance net, as shown in Figure 6 below.

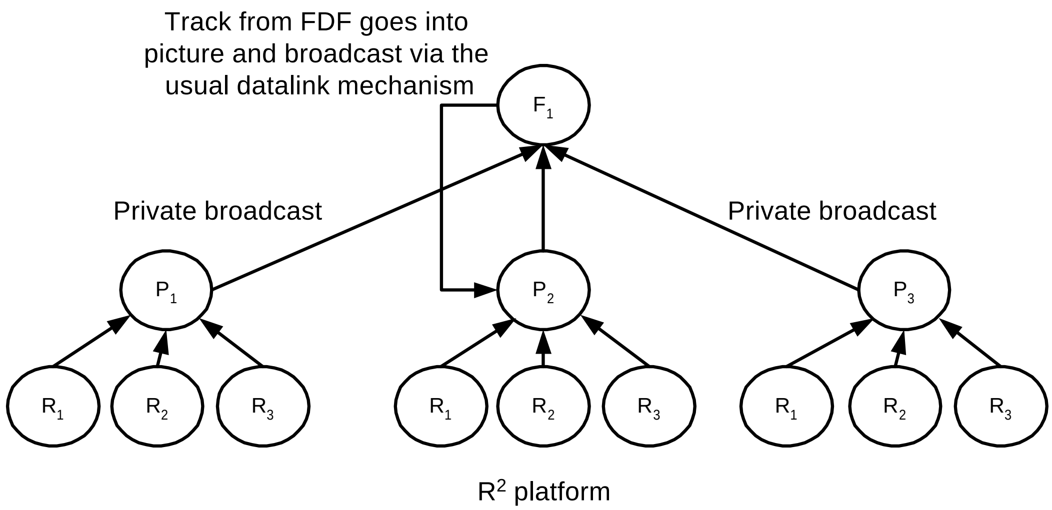

Figure 6: Fusion of Supplemental Private Track Reports

A further source of confusion is the definition of height. Height above the tangent plane, (calculated from the elevation and range) is not the same as height above the Earth. This is particularly important in data link processing because each contributing platform has its own tangent plane and the link picture covers a much wider area over which the curvature of the Earth is more significant. The standard is based on WGS-84 and is supposed to be the normal height from the WGS-84 ellipsoid. For most picture compilation purposes, assuming that the sea is at zero height gives acceptable accuracy, and even a spherical Earth approximation will work with care, but there are applications where this is insufficient.

Different sources provide different heights. IFF and data links can provide an actual height as measured by the aircraft. Situation assessment can provide height ranges based on behaviour or identity. These heights have errors with different characteristics and causes: barometric variations and refraction to name just two. Therefore, the source of the height data needs to be considered too. The potential for deriving contact height from the intersection of tracks from 2-D radars exists but the complications are many and further work remains.

4.4 *Force Picture Co-ordination*

The human factors aspects of force picture compilation have been studied in order to obtain an understanding of the human decision-making processes and the management of data uncertainties in force tactical picture compilation. This has helped to establish the principles that are being used to guide the design of the FDFTD human-computer interactions, particularly for data conflict resolution, in order to ensure that an acceptable system is developed.

As the tactical environment changes and the fused perception of the environment evolves, conflicts can arise in the interpretation of the sensor data and its subsequent fusion. Deconfliction within a single Unit is relatively straightforward and can be achieved in many instances by the computer system alone. However, with a distributed force environment the management of conflict resolution will be more involved owing to the communication latencies and limited capacity of the data links. Differences may also occur in the local tactical picture and other Units' pictures as a result of different conclusions being drawn from the data available to each.

Because the TQ is calculated with regards to the accuracy of the geolocational information only, it is possible, and very likely, that the R^2 will be assigned to a platform whose identity information is poor. There are mechanisms in place which allow for the identity information to be updated by the source platform in response to additional identity information being received from other Units, but this is currently a time consuming process.

4.4.1 *Conflict Resolution*

The resolution of data conflicts is currently being investigated and has included a study with representative users to ascertain the type of conflicts that arise in compiling a force tactical picture and the processes that humans use to resolve these conflicts. The aim of the study was to gain an understanding of force data conflicts and team decision-making aimed at resolving these conflicts, i.e. the processes adopted and the information required. The output from this study was used to inform the degree to which automation could be implemented to assist in data conflict resolution and the form it could take.

There were two stages to the study. The first was to establish an outline process for data conflict resolution, initial information requirements and types of conflicts, and the relevant team members. The second stage consisted of a walkthrough to provide more detail on the process and the information used to resolve data conflicts. Initially, this study covered all three warfare environments (AAW, ASW, ASuW), however, early on it was decided to focus on AAW as this supported more directly the rest of the work looking at automating force data fusion.

Knowledge was elicited for the first stage of this study from two different sources: literature [O'Hare *et al.*, 1998; Militello & Hutton, 1998; Adelman, 1998; Guzzo *et al.*, 1995; Klein, 1998; Hollenbeck *et al.*, 1995] and documentation, and Subject Matter Experts (SMEs). Both sources provided information on the four elements that were the focus of the study: the team members; the types of data conflict experienced in force picture compilation; the conflict resolution process; and the information required to make effective decisions. The literature and documentation provided information on force picture compilation and resolution, and the theory on team decision-making. Discussions with SMEs defined the nature of the conflict resolution process and information used to reach decisions.

The second stage of the study was scoped during detailed discussions with SMEs about the process. The process was defined as having two elements: picture compilation, or data co-ordination; and situation assessment. The latter element is the province of the AAWO and involves many aspects that are essentially human. This element would have required more effort than was available in this study to capture in detail and, as the data co-ordination element fitted in better with other work in the area, it was decided that this first element would be the focus for the walkthrough. On this basis, an existing rapid prototyping facility was adapted for use as the networked computer system and to provide scenario generation.

Six SMEs (RN training instructors from HMS Dryad) participated in the walkthrough, carrying out their usual picture compilation duties and activities during an Anti-Air Warfare scenario, which contained five contrived conflict situations: one episode of loss of gridlock; two aircraft acting suspiciously; and two pieces of false information. (Other conflicts also occurred, created by the SMEs.) The SMEs were allocated to one of three 'ships' fulfilling the roles of Tactical Picture Supervisor (TPS) and Electronic Warfare Director (EWD), with the AAWC ship having a Force Track Co-ordinator (FTC) and Electronic Warfare Co-ordinator

(EWC). Following a briefing and training on the unfamiliar system interface, the SMEs were video taped whilst running through the forty minute scenario. There was then a debrief consisting of further discussion on the process, team members, information required and the types of conflict that might occur. The SMEs were also asked for their opinion on what could be automated and how automation could be implemented.

The videos from the walkthrough were analysed using a video analysis tool focusing on the contrived conflicts, in particular the two suspicious aircraft, due to time and resource constraints. The findings from this analysis were combined with the information gained from the first stage of the study to provide a detailed description of the process and information requirements.

There are two areas where data conflict can occur: picture compilation; and situation assessment. Picture compilation is concerned with track information as provided by sensors and, as such, conflicts are largely resolved based on *extrinsic* knowledge. Situation assessment utilises the same information combined with information from other sources to reach conclusions, but the resolution of conflicts is more heavily influenced by *intrinsic* knowledge, such as expectations and the perceived reliability of sources. Picture compilation conflicts are therefore more concerned with the data from the sensors and the combination of the data and less concerned with opinion than are situation assessment conflicts.

Discussions with SMEs revealed that force data conflict occurs when a ship's information is different to that of other ships as presented in the force picture. Data may come from a number of sources, such as radar, ESM, IFF, and inform on a number of aspects of a track, such as position and identity. In the AAW domain, ESM is the primary information source, backed-up by radar and with IFF providing secondary evidence. Conflict resolution is achieved by utilising these information sources from: the ship with the best equipment fit; personnel in whom confidence is high; the best placed source; and on occasion, further information gathered by another source.

At present it is only possible to state at a high level the form that automation should take; at a lower level the human-computer interface needs to be designed based on high level decision-making requirements. The following recommendations are initial high-level decision-making requirements:

- Automation for force data conflict resolution should take the form of a decision-aid, to assist the human in reaching a decision i.e. resolving a conflict.
- The decision aid should not constrain the human decision-making process. Human biases and intrinsic knowledge should not be designed out of the process.
- The decision aid should present the user with details concerning the data/information source in order to determine the source and therefore the data/information to use. The source details should consist of position and capability.

Functionality will be required to provide the ability to detect that a conflict has arisen. The most straightforward conflict is that one Unit is supplying a different identity assessment on a vehicle. A more complicated example is the detection that two tracks have been shown to 'bounce' when in fact they have crossed hence FTNs will need to be reassigned.

Once a conflict has been detected this functionality is required to take actions to resolve it. The simplest solution is to indicate the conflict to the operator who can then decide how to resolve it and take appropriate action. However, the machine can assist with the resolving of conflicts by exchanging information (with other platforms involved with the conflict) that it is party to but the other Units are not. Units can then enter a dialogue to negotiate/decide on how to resolve the conflict. This implies that each Unit is continuously assessing the force tactical picture against its own information.

5. **System Design**

A detailed specification [O'Shaughnessy] for the FDFTD was produced and forms the basis of the demonstrator's design and subsequent development. This specification has been elaborated to produce the implementation specification for changes to CMISE for the new functions required and to ensure correct behaviour when operating in a force of Units. The objectives in the creation of the FDFTD are to:

- automate the production of a common force opinion for contacts;
- automate the resolution of differences between force and local opinions of contacts;
- automate the integration of sporadic (e.g. stealthy or manoeuvring) contacts;
- improve the positional accuracy of contacts by allowing an aggregate position to be produced by combining reports from different Units;
- increase flexibility and resilience by allowing all Units to contribute concurrently to the force tactical picture rather than restricting them to specific roles;
- improve the utilisation of the available communications capacity by the use of knowledge-based techniques to control the information exchanged.

The FDFTD is an interoperable system enabling flexible single and multiple Unit operation over a tactical data link. For reasons of accuracy, reliability and compatibility the JTIDS/Link 16 tactical data link was selected as the communications bearer for the demonstrator. The current data link, Link 11, widely fitted to the RN fleet was found to have too high a positional error for tracks and poor gridlocking for accurate force data fusion to be possible, plus low jam resistance and data capacity. JTIDS/Link 16 has the additional benefits of a spherical co-ordinate system (WGS84) and accurate relative navigation based on time of arrival.

All communications bearers are constrained by natural physical laws; hence range, latency and capacity are inter-related such that an improvement in one will lead to a degradation in one or more of the others. For example, an increase in range requires a reduction in carrier frequency, which in turn reduces the total capacity of the carrier. Relays may be used to increase range but are unreliable, introduce further latencies and can significantly reduce the network capacity. Satellites can have very high capacities but are vulnerable to denial or attack and have high latencies in set-up and transmission times. An objective for the system design has therefore been to adaptively exploit available communications capacity for constructing the force tactical picture. In order to achieve this a ruled-based information management process is being developed that integrates closely with the data fusion module.

The data link picture is currently built up on a platform basis (e.g. AAW) overlaid by a C^2 organisation, rather than maximising the available capabilities across the entire force as the tactical situation evolves. With a decentralised architecture, mechanisms are required that co-ordinate and control the behaviour of the overall force capability (i.e. multiple FDFTDs collaborating to build a common force tactical picture). The authority and responsibility for resolving such things as ID conflicts will need to reside at particular points within the system. At present this is achieved by the force command and control organisation (e.g. Force Track Co-ordinator–Air), but with a machine-assisted data fusion process this should be achievable by automated means within the FDFTD platforms.

By sharing and collaborating on the fusion of the force information, networks of FDFTD platforms should be able to realise much improved tactical picture quality and reliability over that of a single platform operating alone. To achieve this, however, requires a coherent set of processes (many of which may reside on disparate items of equipment) across the data fusion platforms. Unless these processes are complementary and work together coherently, anomalies in picture compilation are likely to result.

The ambiguities between platform sensors must be recognised and taken account of within the data fusion rules, this includes constraining the propagation of ambiguities throughout the force. This may be achieved as suggested in [Marriette *et al*] by:

- identifying and segregating poor or unreliable data at the earliest opportunity;
- utilising a more objective and reliable measure of track quality;
- avoiding the promulgation of picture compilation difficulties to the rest of the community;
- maximising the level of agreement in the data held by co-operating Units (complete and detailed agreement is not necessary).

5.1 ***Data Link Picture Compilation***

JTIDS/Link 16 will be integrated into the RN fleet through the fitting of the Data Link Processor System, DLPS. This will provide an interface to Link 16 and the existing data links for the current command systems (e.g. ADAWS on the Type 42 destroyer), and will implement the data link track-correlation rules defined in the relevant standards.

To provide a Link 16 bi-directional communications capability for the FDFTD it was decided to integrate CMISE with DLPS. This has a number of advantages (including management of the data link functions) but also introduces a number of potential problems owing to the overlap in track correlation functions. The FDFTD system has been designed to work around or overcome these.

DLPS and CMISE correlation rules differ as CMISE uses all tracks involved in correlation to support and confirm a multi-track. CMISE correlates both positional and non-positional information to derive a multi-track, this in turn supports a vehicle with identity and state. DLPS only merges non-positional information. If the tracks correlate then DLPS effectively deletes one track, keeps the other, but merges in the non-positional information and applies this to the track kept. The DLPS correlation rules are there to maintain data integrity and for load management, rather than for data fusion.

The FDFTD is required to fuse local sensor information with the remote tactical data link picture provided by DLPS and information from other FDFTD Units to produce a force tactical picture. This requirement builds on the existing data link STANAGs that are well understood and implemented within NATO, and allows early demonstration of the CMISE enhancements.

Integrating remote data into a fusion process and transmitting fused data to other Units introduces new problems into the fusion process. This arises because of the collaborative nature of the force and dispersion of the force's data. It is not simply a case of transmitting data at will and fusing in data without consideration of its origin. The fusion process must take account of the protocols for transmitting and receiving data (e.g. reporting responsibility). For tactical data links these protocols are defined by the prevailing STANAG. The protocols for JTIDS/Link 16 and the fusion processes of the CMISE DFM have been examined in detail and a means to achieve distributed data fusion has been derived. This is described more fully in the FDFTD specification.

5.2 *Force Data Fusion*

The design of the force data fusion functionality is based on the use of:

- the correlation-notification / fusion-request interface to DFM;
- an additional set of vehicle attributes, which are used to hold remote information extracted from received data link messages;
- the source JTIDS Unit (JU) attribute added to track records to identify the ID of the Unit that originated the track.

The design eliminates data incest by careful fusion and release of fused information. It is essential that remote information held in the remote vehicle attributes is not fused in any way with the corresponding opinion held in the local attributes, processing logic within the FDFTD ensures that this does not happen.

DFM provides capabilities to correlate sensor contacts with the current fusion hypothesis, and fuse the new contact into the correct point in the hypothesis, amending the derived hypothesis according to the new information.

In the original single-platform version of CMISE, DFM-correlated sensor contacts were always fused into the current vehicle hypothesis following correlation. Whilst this strategy is acceptable for remote bearings received from the data link, it is not acceptable for remote point tracks which contain information that has been derived/hypothesised from other tracks as they may degrade the Own Unit's opinion and lead to data incest if the derived opinion is subsequently transmitted.

Hence to avoid data incest DFM must not fuse remote point tracks into its hypothesis. Instead remote point tracks must be correlated with the current hypothesis and identified as remote supporters of the vehicles to which they are correlated.

Enhancements to CMISE have provided the capability to defer fusion, and subsequently either discard or fuse tracks into the hypothesis. The FDFTD has made use of this capability to include or exclude the fusion of sensor contacts into the hypothesis, thereby eliminating the possibility of data incest.

To retain compatibility with current systems already on board naval platforms a design was required that matched the functionality of DLPS. Because this means that two independent correlation systems (i.e. DFM and DLPS) will have to interoperate a master-slave design was selected with DLPS as the master and a new CMISE module (FDFM) as a slave following any correlation or decorrelation decisions made by DLPS and interacting with the DFM. The functional behaviour of this design is shown in Figure 7 and follows the sequence below:

a) DFM will receive local and remote tracks supplied via the CSH;

b) DFM will pass these tracks to the FDFM;

c) if DFM needs to correlate or decorrelate any track it will send a correlation confirmation message to FDFM for acceptance or rejection;

d) FDFM will then request that the tracks are correlated or decorrelated by DLPS, depending on the request from DFM;

e) reply received from DLPS to the correlation request;

f) the response from DLPS will then be mirrored by FDFM in response to the correlation confirmation request.

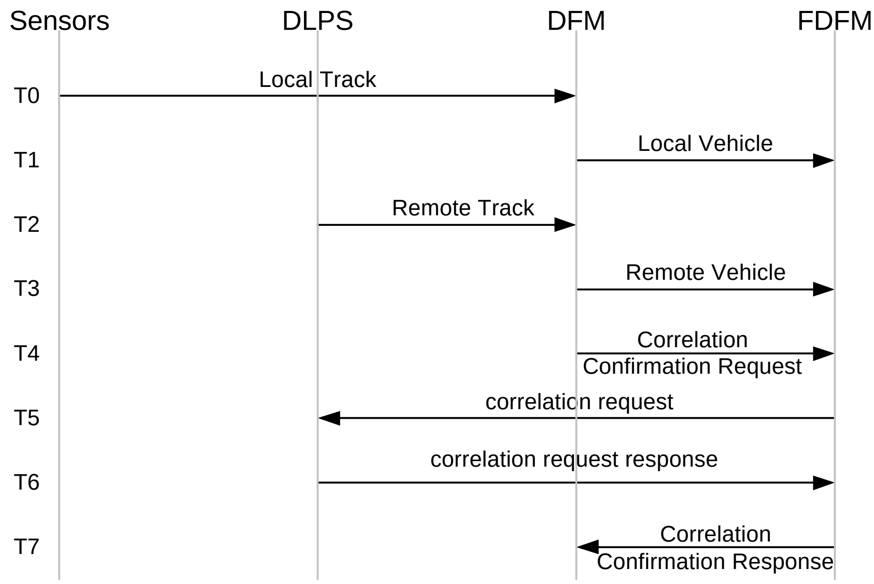

Figure 7: Event Sequence

5.3 *Position Enhancement*

The position enhancement function has been implemented in the new CMISE module, FDFM. This module takes privately reported supporting tracks and mathematically fuses them with the appropriate Own Unit tracks to form an Enhanced Contact Position (ECP) in the form of a pseudo radar point track. This is then be reported onto the CSH for fusion by the DFM into the vehicle hypothesis.

Changes to data link messages that require a modification of the reception processing performed by all Units would adversely impact the interoperability of Units that have not been modified. It is a better practice for such changes to be introduced by the addition of a new message, which can be simply discarded by Units that have not been modified to process the new message without impacting the operation of the Link. It was therefore decided that new messages would be defined and used to communicate the additional surveillance track reports required by the FDFTD for position enhancement.

JTIDS/Link 16 can provide a 'private' communications channel by use of National Messages or Free Text Messages (FTM) over the digital voice channel. The DLPS does not allow the transmission and reception of National Messages over the data links, hence use of National Messages for an operational demonstration afloat is not a viable option. DLPS supports the transmission and reception of free text messages over the CSH. This option marginally increases the overhead for each FDFTD message, as the individual fields in the FDFTD messages are formatted into a set of characters to enable them to be communicated as free text messages. This however enables proof-of-concept demonstration at sea and will have only a marginal reduction in track reporting rates.

To interoperate with non-FDFTD capable Units, FDFTD Units has to implement the link reporting responsibility rules to communicate surveillance track information to non-FDFTD Units. The reporting options for a FDFTD Unit were considered to be:

- aggregate position: derived from the local sensors and supplemental track reports which have been 'privately' communicated from other FDFTD Units;
- local position: derived from local sensors only, with the aggregate position generated locally by each FDFTD Unit.

It was decided that FDFTD Units should report the aggregate position to enable the more accurate information to be made available to non-FDFTD Units in a mixed deployment of Units.

At a later date it is envisaged that additional J-Series messages will be defined to include the additional force data fusion messages in the J-Series message catalogue to reduce the overhead associated with their transmission and enable force data fusion to coexist with the existing Free Text Messaging capability.

A simple software prototype was developed to evaluate the position enhancement process and the protocols to support the exchange of private reports. The algorithms so developed have now been incorporated in the FDFTD for position enhancement of both local-local and local-remote track intersection, and the OOPSDG simulator enhanced to send private reports as FTMs over the voice channel. Significant improvements in contact AOU have been shown to be possible; however, the utility of position enhancements will only be proven once the functionality is exercised using real trials data because of the complexities in the process and the inherent errors in real sensor data.

5.4 *Conflict Resolution*

The CMISE processes for track, multi-track, surface and subsurface correlation determine if two objects correspond positionally within the tolerances permitted. If this criterion is met the identification or classification applied to both objects are examined for compatibility, checking the standard identity, environment, platform type, class and name of each object. The correlation fails if these attributes differ.

It is intended that the combined identity correlation process would use identity confidence associated with the standard identity attached to tracks, multi-tracks and vehicles to aid the decision process to determine a combined platform identity. This combined identity would have a confidence state attached to indicate to the operators the level of probability that the two objects are the same. These confidence states may be confirmed, probable or possible identities and would be displayed on the force tactical picture beside the platform.

The standard identity is the first indicator of the potential threat, some correlation processes presently use this attribute to immediately confirm a tentative link. A combined identity of differing environmental attributes is undesirable, as they are mutually exclusive. The combined identity will therefore use the standard identity and environment supplied, and combine platform type, class and name attributes.

Enhancements to the force data fusion process will aid conflict resolution by correlating objects where there is uncertainty connected with that correlation. The standard identity and environment would be the same, but differences in other identity attributes would be displayed to the operator. These combined and enhanced identities will permit operators to view any uncertainty connected with an object, to monitor these uncertainties and take appropriate action to clarify the situation if they consider it necessary. These processes should also establish operator confidence in the system. The representation and management of data uncertainty for operators has been study and various guidelines derived for the human computer interaction processes and the display of uncertain data.

The force picture co-ordination process is being developed in three phases. Phase 1 will be the implementation of the conflict detection and resolution process in accordance with the appropriate equipment specifications. Phase 2 will add a conflict resolution operator window, which will appear on reception of a conflict alert, this will provide the operator with the ability to select the identity believed to be correct. Phase 3 will expand on Phase 2 by providing the operator with a greater amount of supporting information to aid their decision process. The study into data conflict resolution found that operators achieved conflict resolution by using information such as best equipment fit and best placed source. This phase will provide such supporting information to the operator and through additional functionality, possibly rule based. Phase 1 is currently being implemented as an enhancement to CMISE following the specifications and standards for DLPS, JTIDS and STANAG 5516.

5.5 *Information Management*

The number of reports on an object should be adjustable depending on the quality of the individual reports and an assessment of the worth in adding more data to the fusion process. The number of reports should also be governed by the communications capacity prevailing at the time and the importance of the reporting data, e.g. contact identity could be used to dictate reporting frequency.

An information management policy is being researched to optimise the use of the communication links with other Units and ensure that the best quality data is made available in a timely manner to the most appropriate processes. This will require the reliable identification and categorisation of the data and management of the data flows.

Information escalation is the process by which the level of information communicated within a force, on objects detected by the Units of that force, is increased, and conversely decreased, depending on the individual ‘tracking’ requirements of the detected objects.

The purpose of different, selectable, information escalation levels is to ensure that best use is made of the available communications capacity and recipient Unit processing, by controlling the volume of information passed amongst the force Units without degrading the tactical picture produced.

The information requirements for each object detected by a force will differ and change with time. By applying the information escalation levels on a link-track by link-track basis, while one group of link tracks may require substantial amounts of information to be communicated others will require minimal amounts. Thus, at any point in time the communication and processing loading will be at the minimum required for the generation of an acceptable force tactical picture.

Information Management functionality to support intelligent management of data link capacity is presently being designed and will include the capability to decrease the update interval of selected tracks to make sufficient capacity available for the additional private reports for position enhancement. Intelligent use of the link capacity should be achieved by basing utilisation on operational needs, trading off reporting frequency against positional accuracy. JTIDS allows an operator to nominate specific air and surface tracks derived from own sensor data or non-C2 target data for Variable Update Reporting (VUR). It is planned to use this function for Information Management to control the reporting rates of tracks and hence optimise the data link load. In addition, transmission track filters may be used.

Information to be conveyed around the force is situation dependent (i.e. platforms, locations, hostiles, force disposition, etc), hence it is very unlikely that a generic protocol could be found that would cope with all situations. The use of a ruled-based approach, which can be tuned, is therefore considered to be the most appropriate for the management of information flowing around the force, and is currently being investigated as part of the functionality.

5.6 *System Architecture*

The principal components of CMISE with their interconnections to the platform equipments are shown in Figure 1 above. This has remained essentially unchanged for the FDFTD with the exception of the inclusion of the DLPS system to provide the JTIDS/Link 16 data link capability and the addition of a new module, FDFM, implemented as a TPS client.

Interoperation between data fusion platforms, and to a limited extent with non-FDFTD platforms, has been achieved through the integration of a JTIDS/Link 16 capability. This provides a bi-directional data link capability of sufficient capacity and jam resistance to enable the exchange of sensor reports and management messages to achieve automated distributed data fusion.

Earlier research [Richards] identified a number of system architectures for force data fusion. Working from these options and taking into account work in related areas [Winnicott; Griffith & Hooper; DERA1] a distributed design was selected as this has significant operational benefits (e.g. lowest vulnerability to hostile disruption), provides the greatest flexibility for investigating different data exchange structures whilst remaining compatible with legacy systems, and is compatible with the network-centric model of tactical data links. Each FDFTD will therefore have an identical set of functions, which can be used in various combinations to fulfil a given platform’s role required at the time of operation to cope with differing command and force structures.

The conceptual architecture derived to achieve force data fusion is illustrated in Figure 8. The architecture uses the existing CMISE local data fusion process to fuse organic sensor tracks to produce the local force tactical picture hypothesis, with new processes for force data fusion and information management.

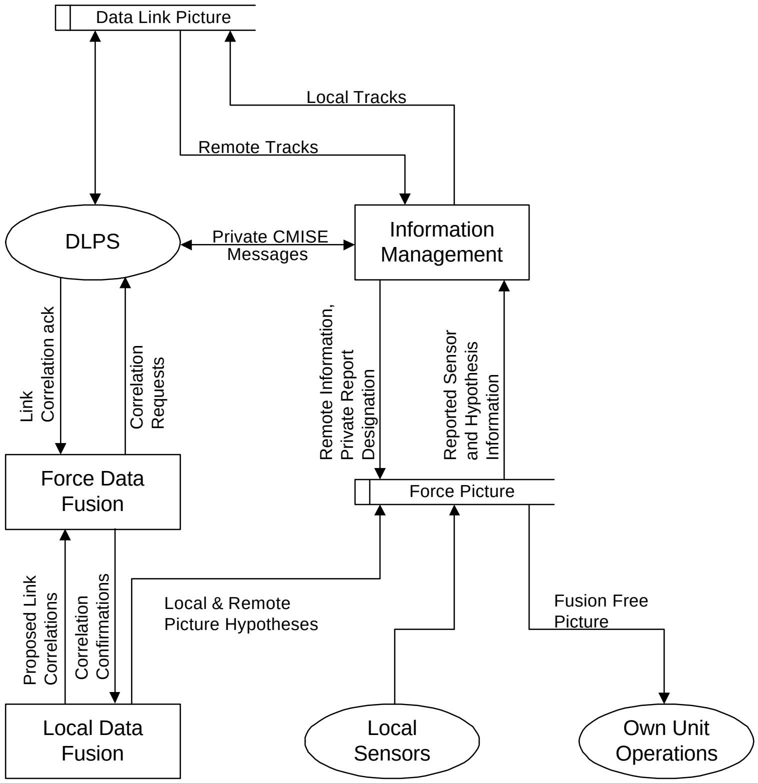

Figure 8: FDFTD Conceptual Architecture

The DLPS participates on Link 11, Link 16 (via JTIDS Terminal) and Satellite Link 16 (STDL) to produce a common Link tactical picture which is correlated with the Own Unit's tactical picture and the tactical picture held by the other Link Participants. The DLPS uses the Enhanced Tactical Picture Broadcast (ETPB) protocol [MOD] to interface to the platform's CSH to access the Own Unit's tactical picture and supplement it with the remote tactical picture. A common track picture for all Combat System equipment on the CSH is achieved via conformance to the ETPB specification. The FDFTD interfaces to the DLPS via the CSH using a sub-set of CSH messages defined in the relevant Data Exchange Specification (DES) in order to send and receive link tracks.

The correlation function provided by DLPS may be switched off to allow the command system to correlate tracks. However, the DLPS is required to be the final arbiter of all proposed correlations, both those proposed locally and those proposed by remote Units. Consequently it is designed to automatically reject any correlation that violates any defined Operational Consideration Constraints (OCC), independently of the DLPS correlation function status.

It is this ability to override the local-remote correlation function of DLPS that has been exploited by the FDFTD to enable force data fusion to be achieved. The FDFM and DFM together identify local-remote correlations and report these to the DLPS, which then ensures the standard data link protocols (e.g. reporting responsibility) and OCCs are enforced.

6. **Development Programme**

The FDFTD is a three-year development project and has recently completed its second year. The specification was produced in the year prior to the start of the project and was derived from research into co-operative picture compilation techniques. Implementation of the enhancements to CMISE is underway and an early representative demonstrator of up to three Units has been produced that automates the fusion of local with remote tracks, release of fused vehicles onto the data link, and simple position enhancement of tracks all via a simulated Link 16 network. Current work is developing the fusion of ESM tracks into the force picture and automation of the force picture co-ordination process.

The FDFTD is being achieved through the proven development processes that have been evolved over a number of years on the CMISE programme. The specification is being elaborated into a set of System Change Requests (SCR) through the knowledge acquisition [DERA2] activity involving the Chief Design Authority and Chief Systems Engineer, and constitute the detailed requirements for enhancements to CMISE. Along with SCRs generated by other research items, these SCRs are scheduled into the development programme for implementation in progressive releases of CMISE.

Development of CMISE is an on-going activity and follows a rolling programme of enhancements and corrections. Development of the FDFTD is synchronised with the supporting releases of CMISE in order to match this programme and enable progressive development. The overall approach of the research programme for the FDFTD is evolutionary. This enables an on-going investigation and experimentation activity to exist in parallel with the engineering development work for the CMISE enhancements. The performance and feasibility of the enhancements can be examined as part of the research allowing further enhancements and modifications to be made throughout the programme.

CMISE systems are developed and tested using the OOPSDG simulator. This provides simulation of the operational environment and sensor contacts. OOPSDG has been enhanced to support multiple FDFTD systems interoperating over a simulated Link 16 network. This enables the data link messages to be transmitted between multiple FDFTDs without the need for complex and expensive operational equipment.

OOPSDG also has a simple emulation of DLPS. This enables multiple FDFTD Units to exchange Link 16 J-series messages and provides a representative DLPS for each Unit. OOPSDG is currently being enhanced to provide further DLPS functionality and a higher fidelity representation of the data link, i.e. network capacity and latency for given Unit configurations, to give more accurate behaviour.

7. **Experimental Programme**

The FDFTD has reached a stage of development where it is now appropriate to start measuring the quality of the compiled force tactical picture and the performance of the automated FDFTD functionality. It is also intended to perform case studies with military users in order to canvass the views of both operators and command of the system’s utility. Results from these studies will guide further research and development, and provide measures of performance with representative users ‘in the loop’.

The FDFTD aims to improve information accuracy, timeliness, and performance but this needs to be related to military effectiveness. This is a difficult task due to the many factors that relate improved information to improved combat effectiveness, these factors [Waltz & Llinas, 1990] include:

- cumulative effects of measurement errors that result in targeting errors;
- relations between marginal improvements in data and improvements in human decision making;
- effects of improved threat assessment on survivability of own forces.

The Military Operations Research Society has recommended a hierarchy of measures [MORS] that relate performance characteristics of C^2 systems (including fusion) to military effectiveness. These measures are divided into four sections:

- Measures of Force Effectiveness: how a C^2 system and the force of which it is a part performs military missions.
- Measures of Effectiveness: how a C^2 system performs its functions within an operational environment.
- Measures of Performance: how the C^2 system behaves.
- Dimensional Parameters: the properties whose values determine system behaviour.

Measures of Force Effectiveness quantify the ability of the total military force to complete its mission. These measures include such things as rates of attrition, outcome of engagements, and weapons on target.

A programme of experiments using synthetic and trials data is planned in order to assess the system's performance and tactical picture quality. The four requirements for a force tactical picture identified by [Quigley] constitute the basis for evaluating force data fusion, these are:

- all Unit commanders operating in the same area must have reasonably consistent pictures, i.e. with no significant difference;
- the picture must be complete regarding friendly and neutral objects and as complete as possible regarding hostiles;
- the picture must be up to date;
- the picture compilation and dissemination system must be workable in strict EMCON and severe ECM conditions.

The metrics derived from these requirements and the MORS measures above for the evaluation of the FDFTD are shown in Table 2 below. These metrics when applied to an evolving force tactical picture will provide a quantitative assessment of picture quality and errors. Feedback from such assessments will help direct the research by identifying where shortfalls may exist and provide a gauge for fusion effectiveness.

7.1 *Scenario Methodology*

The number of possible scenarios required to evaluate the FDFTD across a sufficiently wide range of parameters is clearly limited by time and cost constraints. A structured approach for the selection of scenarios is therefore required in order to maximise use of available resources and ensure effective testing.

For force data fusion, scenarios must not only test the fusion rules but also the information management, the distributed architecture and the private communications to determine any changes or enhancements that may be required to make the system more effective and to quantify any improvements that may result.

The method to be adopted for the work is based on the study approach [Mathieson *et al*] originally developed for naval electronic warfare, which identifies the particular characteristics of scenarios most likely to have a significant impact on a given problem domain. The characteristics that, at present, affect the outcome of the fusion process are portrayed diagrammatically in Figure 9.

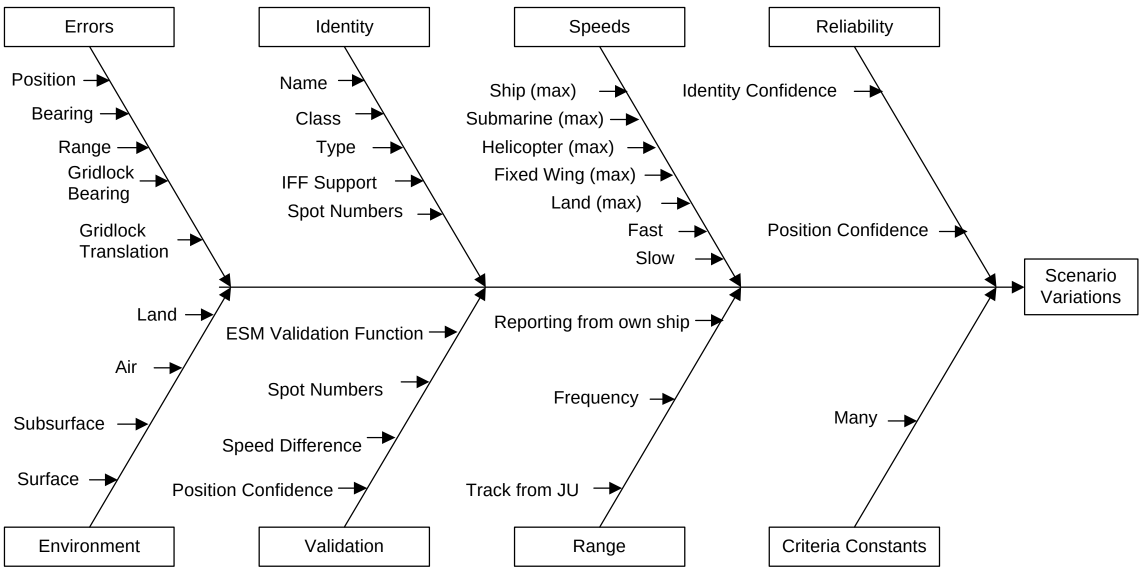

Figure 9: Scenario Characteristics

Table 1 shows some examples of scenario characteristics. These characteristics are considered as axes on a multi-dimensional matrix where each axis is a variable feature of the scenario, such as terrain or hostilities, for which significant values can be defined.

Category	Characteristic	Significant Values
Geography	Weather	Affect on Air Sorties
	Latitude	Utilisation of Satellites
Own Force	Force Structure	Infrastructure Available
	Level of Activity	Loading on data links
Status	State of Hostilities	ROE roles

Table 1: Categorisation of Characteristics

From the completeness of the characterisation matrix the chosen set of scenarios can be demonstrated to be adequate for the evaluation task and highlight where new scenarios need to be developed. A full matrix defines all significant scenarios for a given problem domain, a partial matrix can be produced for a given sub-set of cases. Figure 10 illustrates a limited scenario coverage within a characterisation matrix.

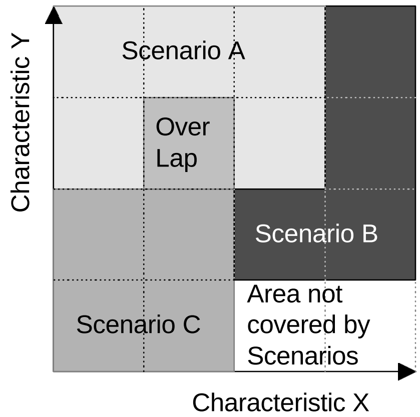

Figure 10: Characterisation Matrix

There are six possible combinations (dependent on track type) that DFM uses for either correlation or association. These combinations are:

1) radar to radar correlation either from Own Unit or other Units;
2) radar to bearing correlation either from Own Unit or other Units;
3) bearing to bearing association either from Own Unit or other Units;
4) three bearings from three platforms, the intersect point is positive evidence for correlation;
5) timescale information association where the same platform observes a contact in roughly the same area but at two different times;
6) correlation history, where two or more contacts follow each other exactly for a fixed time period there is a possibility for correlation.

The possible combinations for DFM correlation or association between three platforms can be calculated using:

$$^{n}C_{r} = \frac{n!}{(n-r)!r!}$$

For *r* successes occurring in *n* trials, where n = types of position information + 1, and r = number of types combined. For four types of position information (point, bearing, region, null) and a fifth type of either point, bearing, region or null then combining three of these types there are twenty possible combinations.

$$^{6}C_{3} = \frac{6!}{(6-3)!3!} = 20$$

These combinations will be used to evaluate the fusion functionality of the FDFTD for given sets of representative scenarios.

7.2 *Performance Evaluation*

An approach previously used to evaluate data fusion performance was based on a sequence of snapshots at defined intervals that are compared against a previously prepared ‘standard world’. This is labour intensive, slows down the evaluation process and is difficult to achieve repeatably.

An automated method of data fusion performance measurement has been developed that uses a simple scenario that is simulated by OOPSDG. As a synthetic scenario is used rather than one based on data collected from sea trials, the ‘ground truth’ is available. This method is based on three elements:

1) OOPSDG provides a list of all scenario objects with all tracks that should be correlated to these objects;
2) DFM provides a list of all vehicles held with details of all tracks correlated and identities established;
3) an analysis program (called the Performance Analysis Tool) compares the DFM output with the OOPSDG scenario objects’ details and derives a set of performance metrics.

The performance metrics include:

- correlation error rate – the number of correlations that failed but should have correlated correctly;
- extent of correct correlation – the number of correct correlations that never occurred;
- object fragmentation – the number of vehicles that should have been fused but were not.

The evaluation of the FDFTD will take the form of a scenario being executed on several different system configurations. Examination of the configuration permutations resulted in the derivation of the system configurations to be used for the evaluation. The baseline will be the manual fused picture using all-source manual tactical picture compilation including the tactical datalink. The configurations to be evaluated will be all-source data fusion with full use of tactical datalink with and without position enhancement.

The baseline configuration will be used as a standard against which to evaluate the performance of the other configurations. The results of the configurations will be compared against the baseline to determine if any improvement or worsening in the tactical picture is present. The results will take the form of values representing each of the evaluation metrics as defined in Table 2 below.

Recorded data requires analysis before being used by OOPSDG to produce a scenario, OOPSDG can then make models follow tracks from this analysed data. These tracks can subsequently be combined to produce a scenario. OOPSDG has been used to design scenarios to evaluate specific areas of interest. A capability for live replay of recorded data has also been implemented that provides highway data to the CSH equipments in real time. This capability has been extended to the force level by enhancing OOPSDG to synchronise the data replay to multiple Units.

Evaluation of the FDFTD has commenced and is planned to cover the following steps with step 1 having already been completed. The plan also contains assessment work that would be required for future releases to demonstrate military worth.

1) Assessment of radar parameters

Calibrate the modelled radar parameters used in OOPSDG to represent actual parameters obtained from radar systems.

2) Familiarisation with the FDFTD operation

Provision of an adequate period of time to enable the FDFTD personnel to become competent to perform the evaluation.

3) Checking of the FDFTD Position Enhancement functionality

Perform validation of the Position Enhancement functionality before the assessment of picture quality and position improvement.

4) Stress Testing of the FDFTD

Test the FDFTD using maximum number of contacts, with high manoeuvrability, close proximity, and track convergence or crossing.

5) Picture Quality Assessment

Evaluate the picture quality using the evaluation metrics, while running the defined scenario(s) across different force platform configurations.

Category	Requirements	Description	Measure
Measures of Effectiveness	Accuracy of Position	Measure of Position Accuracy	Track Quality or Variances
	Accuracy of Identity	Measure of Identity Accuracy	Standard ID or Vehicle ID
	Orientation	Target orientation reference to own-ship	Relative Target Heading
	Reduction in Operator Load	Free operator time by reduction in load	Increased operator effectiveness
	Timeliness of Information	Process information in a timely manner	Tactical Picture update rate
Measures of Performance	Communication Time Delay	Timeliness of datalink information	Track Update Rate
	Alert Rate	Alert Rate over a fixed period	Alerts per minute
	Identification Probability	The correctness of identification	Standard Identity
	Identification Range	The distance at identity decision	Data miles
	Sensor Spatial Coverage	Area Covered	Percentage Coverage
	Target Classification	The correctness of classification	Classification
	Target Range	The distance at first detection	Data miles
	Detection to Transmission	Time from detection to transmission on datalink	Seconds
Dimensional Parameters	Surveillance NPG users	Datalink Capacity Factor	Number of Platforms
	Surveillance NPG Timeslot allocation	Datalink Capacity Factor	Number of Timeslots
	Track output rate	Number of tracks output on datalink	Tracks per Second

Table 2: Evaluation Metrics

The Performance Analysis Tool is to be enhanced to cope with multiple Unit recordings and will be used to measure the performance of the force data fusion process. Recordings of a ship's radar tracks from a recent trial have been analysed to obtain statistical measures of track errors in order to calibrate the sensor models within OOPSDG before commencing the evaluation phase.

8. **Plans & Exploitation**

The current plans for the FDFTD are to complete development of the system by the end of December 2000 and then to perform laboratory experiments using recorded sea-trials data and military users in order to baseline the force tactical picture quality and performance achieved. Consideration is also being given to trials at sea to test the system in operational conditions.

The outcome of the research will be guidelines for best practise for automated data fusion for force tactical picture compilation that can be exploited for existing and future operational systems that will provide improved situational awareness and, potentially, reduced manning. Intentions for further research include extending the FDFTD functionality to exploit sensor data from airborne platforms, such as unmanned aerial vehicles and stand-off surveillance aircraft, fusing this data with the host platform's sensor data before release onto a tactical data link. This research will support the current drive to improve the integration of Joint forces, especially in support of the new doctrine of manoeuvre from the sea, within the context of network-centric warfare.

9. **Conclusion**

If the UK is to maintain its military capability in the face of a more complex and uncertain threat then continued advances in technology must be assured. As the threat evolves shortfalls in the areas of force-level operations can be expected to deepen. This necessitates that applied research is conducted to resolve these shortfalls and identify enhancements to operational effectiveness to regain the military advantage. The work on data fusion of the force tactical picture is endeavouring to address one important area of operation effectiveness through the practical application of knowledge based systems.

It is highly likely that automated techniques for compiling the tactical picture will eventually be used in operational systems at sea, the requirement for these systems to be full participants in tactical data links will therefore become inevitable. The use of tactical data links by the force data fusion research will ensure that the work has a practical foundation and application hence providing insight on the use of data links for distributed data fusion.

The knowledge and experience gained by this research should provide a strong basis for any proposed changes to current and future data links and Combat Systems. It may also be used to guide formation of any future STANAGs for distributed data fusion and automated force tactical picture compilation.

The FDFTD has already achieved a level of automated force picture compilation over a tactical data link and when completed should provide a realistic testbed to investigate force-level data fusion techniques. This will enable trade-off studies between different fusion approaches to be performed, the impact on the Combat System of force-level data fusion to be assessed and the technological limitations of existing and future operational systems in the area of force tactical picture compilation to be established.

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