

A Beginners Guide to Decentralised Data Fusion

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1 Introduction

This document provides a short and accessible introduction to decentralised data fusion and its application in the ANSER project. Demonstration of decentralised data fusion is the first of the three main objectives of the ANSER project (which also include demonstrations of simultaneous localisation and map building (SLAM), and autonomy). This document is intended to introduce new technical and management staff to the area; to explain the motivation for studying decentralised systems, to provide some appropriate mathematical background, and to describe the research goals and expected technical outcomes of the ANSER project.

This is not a formal project document. It is intended to fill a perceived gap in introducing new staff, both technical and management, to the research objectives of the ANSER project. It has enough background mathematics to explain the main issues, but is not intended as a detailed research monograph. It has enough context to appreciate the business issues for BA Systems, but is not intended as a technology insertion or business plan for decentralised systems.

Section 2 explains what a decentralised data fusion system is, how they work, and what the main advantages of such systems are. Section 3 provides a broad introduction to decentralised data fusion theory and algorithms by means of a historical perspective of past work conducted by staff of the ACFR and BA Systems over the past 10 years. Section 4 describes the *technical* goals of the ANSER project as a demonstration of decentralised data fusion theory and the impact this has on future autonomy. Section 5 describes the focus of current research and the future beyond ANSER.

2 Decentralised Data Fusion Systems

2.1 What is a Decentralised Data Fusion System ?

A decentralized data fusion system consists of a network of sensor nodes, each with its own processing facility, which together do not require any central fusion or central communication facility. In such a system, fusion occurs locally at each node on the basis of local observations and the information communicated from neighbouring nodes. At no point is there a common place where fusion or global decisions are made.

A decentralised data fusion system is characterised by three constraints:

1. There is no single central fusion center; no one node should be central to the successful operation of the network.
2. There is no common communication facility; nodes cannot broadcast results and communication must be kept on a strictly node-to-node basis.

3. Sensor nodes do not have any global knowledge of sensor network topology; nodes should only know about connections in their own neighbourhood.

Figures 1, 2 and 3 show three possible realisations of a decentralised data fusion system (these are discussed in more detail later in this section). The key point is that all these systems have no central fusion center (unlike the ‘decentralised’ systems often described in the literature which are actually typically distributed or hierarchical).

The constraints imposed provide a number of important characteristics for decentralised data fusion systems:

- Eliminating the central fusion center and any common communication facility ensures that the system is **scalable** as there are no limits imposed by centralized computational bottlenecks or lack of communication bandwidth.
- Ensuring that no node is central and that no global knowledge of the network topology is required for fusion means that the system can be made **survivable** to the on-line loss (or addition) of sensing nodes and to dynamic changes in the network structure.
- As all fusion processes must take place locally at each sensor site and no global knowledge of the network is required *a priori*, nodes can be constructed and programmed in a **modular** fashion.

A decentralized system is characterised by being modular, scalable and survivable. Together, these give decentralised systems a major advantage over more traditional sensing architectures, particularly in defense applications.

2.2 How does a Decentralised Data Fusion System Work ?

The ability to construct a decentralised data fusion architecture clearly depends on whether it is possible to efficiently decentralise existing centralised data fusion algorithms. For most common data fusion algorithms, this turns out to be possible, and indeed many decentralised data fusion algorithms are, surprisingly, *more* efficient, in terms of both computation and communication, than conventional distributed, federated or hierarchical data fusion algorithms. In particular, the Kalman filter algorithm, for target tracking and navigation applications, and Bayesian methods, for identification and decision making, can both be efficiently decentralised.

Conventional data fusion algorithms employ the common notion of ‘state’ (position, velocity, identity, etc), together with associated probabilities and likelihoods, to fuse data. Decentralised data fusion algorithms rely instead on the notion of *information*, formally defined through both Fisher and Shannon information measures, for continuous and discrete or continuous states respectively.

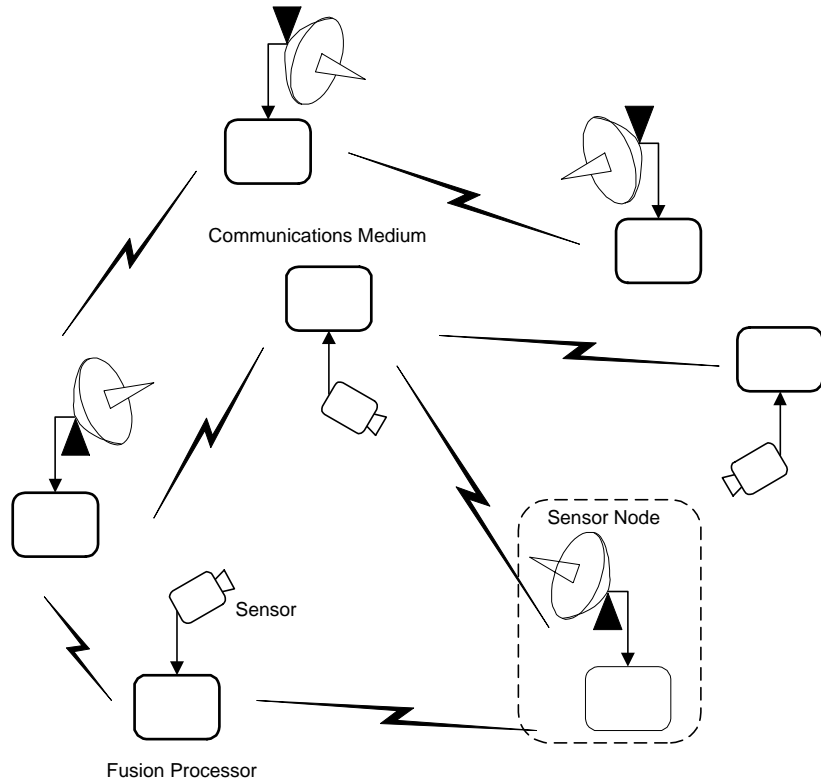


Figure 1: A decentralised data fusion system implemented with a point-to-point communication architecture.

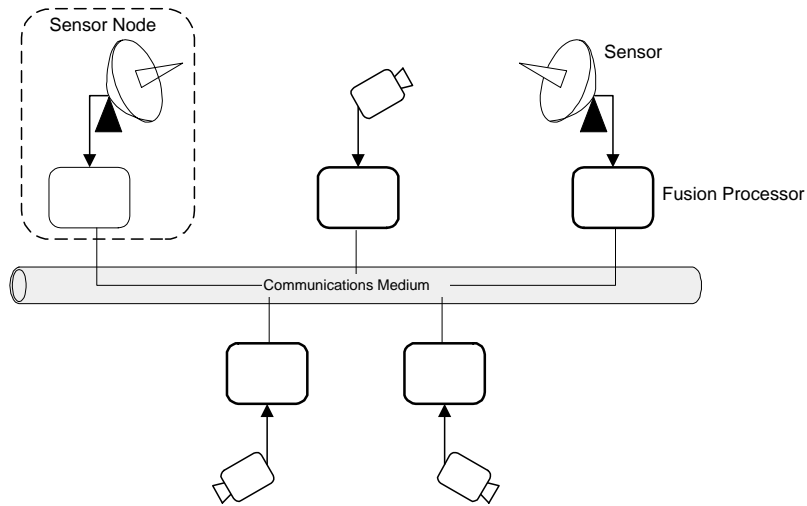


Figure 2: A decentralised data fusion system implemented with a broadcast, fully connected, communication architecture. Technically, a common communication facility violates decentralised data fusion constraints. However a broadcast medium is often a good model of real communication networks.

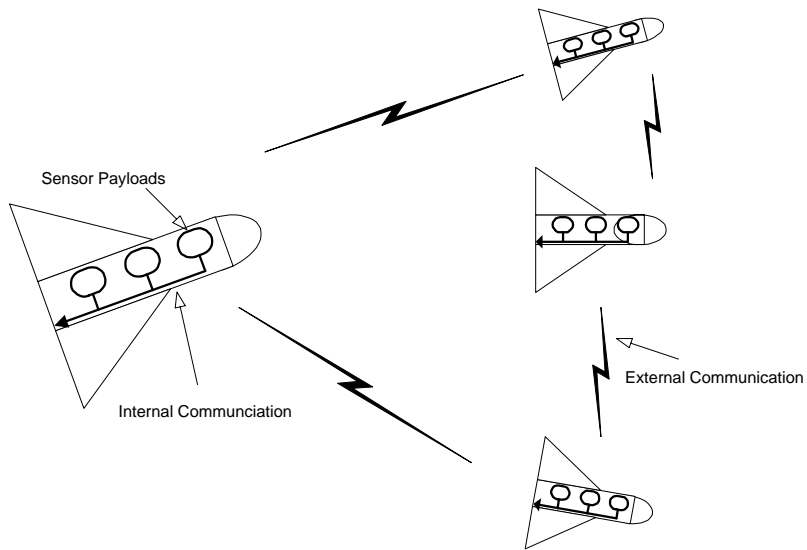


Figure 3: A decentralised data fusion system implemented with a hybrid, broadcast and point-to-point, communication architecture.

Conventional distributed data fusion algorithms communicate state estimates and state estimate probabilities (or covariances). The problem with this is that state estimates are often highly correlated between sources. This is because different sensors use common models of the underlying state and because current estimates depend on common past information. Such problems have resulted in the development of algorithms such as the track-to-track fusion method (in target tracking problems), or the federated filter (in navigation systems). These algorithms are generally expensive and complex to implement as well as leading to poorer results than those obtained from a centralised data fusion architecture.

Decentralised data fusion algorithms communicate information (Fisher and Shannon measures) rather than states and probabilities. The real advantage of an information measure is that it is straightforward to separate out what is new information from what is either prior knowledge or common information. Fusion of information measures is additive. This means that the fusion process is associative (it does matter what order it is done in) and thus can be decentralised without (too much) concern as to when sensors communicate or when they fuse data. Most decentralised data fusion algorithms result in exactly the same state estimates as if the information had been processed in a single central processor; that is decentralisation does result in loss of optimality. This is in stark contrast to conventional data fusion algorithms (such as the Kalman filter) where state fusion is *not* associative and so it matters when and how estimates are constructed.

2.3 Operation of Sensor Nodes and Communication Channels

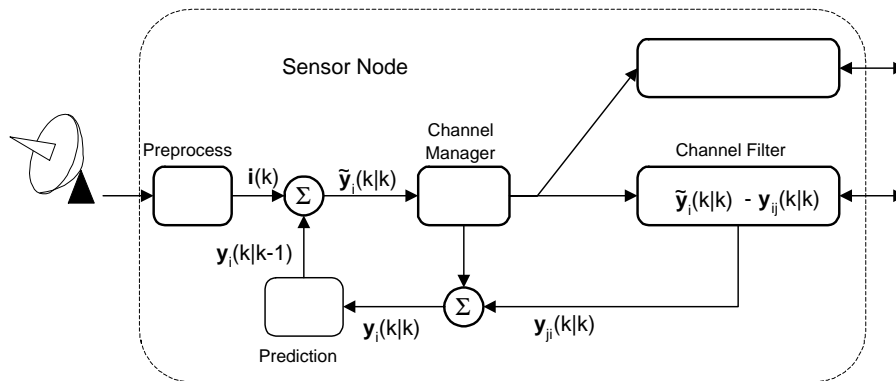


Figure 4: Algorithmic structure of a decentralised sensing node.

Figure 4 shows a typical sensor node, i , in a decentralised data fusion system. The node generates information measures $\hat{y}_i(k | k)$ at a time k given observations made locally and information communicated to the node up to time k . The node implements a local prediction stage to produce information measure predictions $\hat{y}_i(k | k - 1)$ at time k given all local and communicated data up to time $k - 1$ (this prediction stage is often the same

on each node and may, for example, correspond to the path predictions of a number of common targets). At this time, local observations produce local information measures $\mathbf{i}(k)$ on the basis of local observations. The prediction and local information measures are combined, by simple addition, into a total local information measure $\tilde{\mathbf{y}}_i(k | k)$ at time k . This measure is handed down to the communication channels for subsequent communication to other nodes in the decentralised network. Incoming information from other nodes $\hat{\mathbf{y}}_{ji}(k | k)$ is extracted from appropriate channels and is assimilated with the total local information by simple addition. The result of this fusion is a locally available global information measure $\hat{\mathbf{y}}_i(k | k)$. The algorithm then repeats recursively.

The communication channels exploit the associativity property of information measures. The channels take the total local information $\tilde{\mathbf{y}}_i(k | k)$ and subtract out all information that has previously been communicated down the channel, $\hat{\mathbf{y}}_{ij}(k | k)$, thus transmitting only new information obtained by node i since the last communication. Intuitively, communicated data from node i thus consists only of information not previously transmitted to a node j ; because common data has already been removed from the communication, node j can simply assimilate incoming information measures by addition. As these channels essentially act as information assimilation processes, they are usually referred to as channel filters

Channel filters have two important characteristics:

1. Incoming data from remote sensor nodes is assimilated by the local sensor node *before* being communicated on to subsequent nodes. Therefore, no matter the number of incoming messages, there is only a single outgoing message to each node. Consequently, as the sensor network grows in size, the amount of information sent down any one channel remains constant. This leads to an important conclusion: *A decentralised data fusion system can scale up in size indefinitely without any increase in node-to-node communication bandwidth.*
2. A channel filter compares what has been previously communicated with the total local information at the node. Thus, if the operation of the channel is suspended, the filter simply accumulates information in an additive fashion. When the channel is re-opened, the total accumulated information in the channel is communicated in one single message. The consequences of this are many-fold; burst transmission of accumulate data can be employed to substantially reduce communication bandwidth requirements (and indeed be used to manage communications); if a node is disconnected from the communications network, it can be re-introduced and information synchronised in one step (the same applies to new nodes entering the system, dynamic network changes and signal jamming). This leads to a second important conclusion: *A decentralised data fusion system is robust to changes and loss of communication media.*

Together, the node and channel operation define a system which is fully modular in algorithmic construction, is indefinitely scalable in numbers of nodes and communication

topology, and is survivable in the face of failures of both sensor nodes and communication facility.

2.4 Systems of Systems ?

Decentralised systems have two important properties which make them ideal as an architectural basis for the construction of systems of systems. First is the ability to construct a wide variety of system architectures and communication topologies without any change to local fusion algorithms or software operating at a node. Second, is the ability to use the underlying information measures to reason, in a mathematically rigorous manner, about combinations and compositions of systems.

Figure 1 shows a point-to-point communication topology in which each node maintains a number of independent links to adjacent nodes in a network. The channel filter algorithm does not require any knowledge of network topology, and simply communicates new local information to all its immediately connected neighbours. These assimilate communicated data and re-transmit new information to their neighbours. The point-to-point communication architecture is the most general of decentralised data fusion systems architectures, allowing any network topology to be implemented. There are advantages to this structure in allowing for both robustness and nodal autonomy. However, there are disadvantages in both the complexity of communication interconnects, and in propagation delays of information through the network.

Figure 2 shows a broadcast communication topology in which each node is effectively connected to every other node in the system. There is no difference between the nodal algorithms that run in a point-to-point network from those that run on a broadcast system (indeed, it should be clear that any point-to-point communication topology could be mapped on to a broadcast system). The advantage of a broadcast communication system is that it avoids interconnect complexity and information propagation delays. However, the use of a common communication medium goes against a principle of decentralised systems in avoiding any central resource. However, the broadcast architecture does practically implement many existing bus-based and military communication systems.

Figure 3 shows a hybrid broadcast and point-to-point communication topology in which high-bandwidth reliable broadcast communication is used in a local sensor group, and point-to-point between groups. Such architectures can again be implemented without any change in nodal algorithms. Indeed, for any one node on one platform it is, at least algorithmically, not relevant whether information comes from a second sensor on the same platform or from a sensor on a different platform. This allows an almost limitless number of different architectures to be constructed from the same building blocks; nodes could be grouped on a single platform, or across several platforms but on a single task or function; linked in a free topology, or grouped hierarchically; and indeed the topology and groupings could be changed dynamically as tasks require and as resources permit. Fundamentally, the ability to build these architectures is the result of modularity and associativity of the

information structures employed by decentralised data fusion algorithms.

Sensor nodes communicate in terms of dimensionless information measures (dimensionless given the underlying state). This means that it is possible to make every sensor node and channel interface identical and independent of the underlying process or sensing mechanism. Further, because information is defined formally in terms of Fisher or Shannon measures, it is possible to reason, mathematically and *a priori*, about combinations of sensors and systems without knowing any specifics of the sensor or sensing process itself. For example, questions about most informative sensor configurations, hand-off and cuing between sensors, what information to communicate, and management of sensing operations can all be answered in a precise manner. This ability to properly define and reason about systems of systems could provide the essential mathematical tools to develop and deploying future autonomous systems.

3 Decentralised Data Fusion Algorithms

This section provides a brief description of the many decentralised data fusion algorithms developed by staff of the ACFR and BA Systems (Sowerby) over the past ten years. The algorithms are introduced in chronological order as this helps explain much of the motivation for developments and also helps put the ANSER project into perspective.

3.1 The Decentralised Kalman Filter

Work on decentralised systems began in 1989 as part of the ESPRIT project SKIDS. This project aimed to develop a multiple-sensor tracking system for civilian surveillance. The initial impetus for decentralised systems was the development of a decentralised form of the linear Kalman filter. This was achieved by first recasting the usual Kalman filter state estimation problem in information form. Consider a system described in linear form

$$\mathbf{x}(k) = \mathbf{F}(k)\mathbf{x}(k-1) + \mathbf{w}(k), \tag{1}$$

where $\mathbf{x}(j)$ is the state of interest at time j , $\mathbf{F}(k)$ is the state transition matrix from time $k-1$ to k , and where $\mathbf{w}(k)$ is the associated process noise modeled as an uncorrelated white sequence with $E\{\mathbf{w}(i)\mathbf{w}^T(j)\} = \delta_{ij}\mathbf{Q}(i)$. The system is observed by a sensor according to the linear equation

$$\mathbf{z}(k) = \mathbf{H}(k)\mathbf{x}(k) + \mathbf{v}(k) \tag{2}$$

where $\mathbf{z}(k)$ is the vector of observations made at time k , $\mathbf{H}(k)$ the observation matrix or model, and where $\mathbf{v}(k)$ is the associated observation noise modeled as an uncorrelated white sequence with $E\{\mathbf{v}(i)\mathbf{v}^T(j)\} = \delta_{ij}\mathbf{R}(i)$. The Kalman filter algorithm generates estimates for the state $\hat{\mathbf{x}}(k | k)$ at a time k given all observations up to time k , together with a corresponding estimate covariance $\mathbf{P}(k | k)$ as:

$$\hat{\mathbf{x}}(k | k) = \hat{\mathbf{x}}(k | k-1) + \mathbf{W}(k) [\mathbf{z}(k) + \mathbf{H}(k)\hat{\mathbf{x}}(k | k-1)] \tag{3}$$

$$\mathbf{P}(k | k) = \mathbf{P}(k | k - 1) - \mathbf{W}(k)\mathbf{S}(k)\mathbf{W}^T(k) \quad (4)$$

where the gain matrix $\mathbf{W}(k)$ is given by

$$\mathbf{W}(k) = \mathbf{P}(k | k - 1)\mathbf{H}^T(k)\mathbf{S}^{-1}(k), \quad (5)$$

and the innovation covariance by

$$\mathbf{S}(k) = \mathbf{H}(k)\mathbf{P}(k | k - 1)\mathbf{H}^T(k) + \mathbf{R}(k). \quad (6)$$

The information form of the Kalman filter is obtained by re-writing the state estimate and covariance in terms of two new variables

$$\hat{\mathbf{y}}(i | j) \triangleq \mathbf{P}^{-1}(i | j)\hat{\mathbf{x}}(i | j), \quad \mathbf{Y}(i | j) \triangleq \mathbf{P}^{-1}(i | j), \quad (7)$$

and also the information associated with an observation in the form

$$\mathbf{i}(k) \triangleq \mathbf{H}^T(k)\mathbf{R}^{-1}(k)\mathbf{z}(k), \quad \mathbf{I}(k) \triangleq \mathbf{H}^T(k)\mathbf{R}^{-1}(k)\mathbf{H}(k) \quad (8)$$

With these definitions, the Kalman filter (Equations 3, 4, 5 and 6) become

$$\hat{\mathbf{y}}(k | k) = \hat{\mathbf{y}}(k | k - 1) + \mathbf{i}(k), \quad (9)$$

$$\mathbf{Y}(k | k) = \mathbf{Y}(k | k - 1) + \mathbf{I}(k). \quad (10)$$

The information form of the Kalman filter, while widely known, is not commonly used because the update terms are of dimension the state, whereas in the distributed Kalman filter updates are of dimension the observation. For single sensor estimation problems, this argues for the use of the Kalman filter over the information filter. However, in multiple sensor problems, the opposite is true. The reason is that with multiple sensor observations

$$\mathbf{z}_i(k) = \mathbf{H}_i(k)\mathbf{x}(k) + \mathbf{v}_i(k), \quad i = 1, \dots, N$$

the estimate can not be constructed from a simple linear combination of contributions from individual sensors

$$\hat{\mathbf{x}}(k | k) \neq \hat{\mathbf{x}}(k | k - 1) + \sum_{i=1}^N \mathbf{W}_i(k) [\mathbf{z}_i(k) - \mathbf{H}_i(k)\hat{\mathbf{x}}(k | k - 1)],$$

as the innovation $\mathbf{z}_i(k) - \mathbf{H}_i(k)\hat{\mathbf{x}}(k | k - 1)$ generated from each sensor is correlated because they share common information through the prediction $\hat{\mathbf{x}}(k | k - 1)$. However, in information form, estimates can be constructed from linear combinations of observation information

$$\hat{\mathbf{y}}(k | k) = \hat{\mathbf{y}}(k | k - 1) + \sum_{i=1}^N \mathbf{i}_i(k),$$

as the information terms $\mathbf{i}_i(k)$ from each sensor are uncorrelated. Once the update equations have been written in this simple additive form, it is straight-forward to distribute the data fusion problem (unlike for a Kalman filter); each sensor node simply generates the information terms $\mathbf{i}_i(k)$, and these are summed at the fusion center to produce a global information estimate.

To decentralise the information filter all that is necessary is to replicate the central fusion algorithm (summation) at each sensor node and simplify the result. This yields a surprisingly simple nodal fusion algorithm. The algorithm is described graphically in Figure 4. Essentially, local estimates are first generated at each node by fusing (adding) locally available observation information $\mathbf{i}_i(k)$ with locally available prior information $\hat{\mathbf{y}}_i(k | k - 1)$. This yields a local information estimate $\tilde{\mathbf{y}}_i(k | k)$. The difference between this local estimate and prediction (corresponding to new information gained) is then transmitted to other nodes in the network. In a fully connected or broadcast network, this results in every sensing node getting all new information. Communicated information is then assimilated simply by summing with the local information. An important point to note is that, after this, the locally available estimates are *exactly* the same as if the data fusion problem had been solved on a single central processor using a monolithic formulation of the conventional Kalman filter.

In the SKIDS project, a fully decentralised surveillance system was implemented using four cameras and a Transputer based architecture. The network was a fully-connected point-to-point topology. The system was capable of tracking multiple targets (humans and robots). A decentralised data-association algorithm was developed, but this was superseded in later research and so is not described here. A decentralised identification algorithm was also developed but this too was later superseded. The algorithms developed for the SKIDS project are fully described in Bobby Rao's D.Phil. thesis [30], and in the papers [33, 32, 31]. The SKIDS demonstrator, which continued to be refined and operated for almost 10 years, laid the basis for all subsequent work on decentralised data fusion.

3.2 Communication in Decentralised Systems

An essential limitation with the original decentralized Kalman filter algorithm is that it requires the sensor network to be fully connected so ultimately limiting the size of any realisable decentralized sensing system. The need for fully connectedness is a consequence of the assumption that common information between two neighbouring sites is simply the prior information they share.

This observation led to an analysis of information flow in decentralised sensing networks. By introduction of an additional filter associated with each communication link, it was shown that tree connected network topologies can also be supported by the decentralized Kalman filter algorithm. This is described in detail in Stewart Grime's D.Phil. thesis [15] and in [16]. Channel filters, as they became known, also address a number of key issues in data asynchronicity, communications management and network reliability.

Simukai Utete's D.Phil. thesis [39] showed that, within the constraints imposed by the definition of a decentralized sensing network, it is not in general possible to construct a set of filters which can provide consistent estimates across an arbitrary network topology. To overcome this, decentralized routing algorithms were developed to enable construction of tree connected networks from networks of arbitrary topology [38, 41, 42, 40, 43]. Such algorithms maintain both consistency across the estimators in the network and satisfy the constraints of locality and modularity of a decentralized system. Many of these ideas were developed on a large-scale demonstrator as part of the ISSS project. This demonstrator consisted of a model process control system consisting of over 200 sensors linked to over thirty purpose designed decentralized processing sites. The ISSS demonstrator allowed on-line network reconfiguration and software imposed communication bandwidth limitations. The demonstrator was designed to show scalability of decentralised data fusion algorithms to large numbers of sensors.

Further work on communications management has also been undertaken by Rob Deaves of Sowerby research center [9, 10]. This work builds on the idea of a channel filter and other work on information modeling [22] to manage communication between sensing platforms. The work is developed in a military context.

3.3 Model distribution and Control

A second limitation of the original decentralized Kalman filter algorithm is that it requires a complete system model to be maintained at every sensor site. As the size and complexity of a system grows the need for a global model at each site becomes prohibitive. The problem of distributing system models across a sensor network was initially considered by Berg [1, 3, 4, 2]. Starting with a central state model and with the local observation models associated with each sensor node, it was shown that only a locally observable sub-model of the central state model is required at each site to ensure consistent estimates across a network. It was also shown that the transformations of model from central to local sites can be combined to provide a single transformation from one site to another which can be implemented as part of the node-to-node communication mechanism.

An important contribution of this work was in the geometric interpretation of information and the consequent explanation as to why information measures, and not state estimates, are uncorrelated (orthogonal) and thus why information fusion is associative. This result was also exploited in the development of the information gate; an information form of the equivalent data validation or innovation gate commonly used data association algorithms [12, 13, 14]. Data validation is essential in practical data fusion problems in providing a means of associating different internal models to observations made and in rejecting observations that are considered to be outliers or spurious. In decentralized systems validation must often take place remotely from the original observation. Understanding how an observation taken at one site with only a partial local model of the overall system compares to observations taken at another site with a different partial model is

essential in being able to associate and validate information across a decentralized sensing network. This work is also continuing in the development of high integrity navigation systems [18].

A second consequence of the ability to perform model distribution is that it also allows a connection to be made between the decentralized data fusion techniques and the field of decentralized control. In decentralized control, components of an overall system model are distributed amongst a number of sites that both take observations of the world and exert control over the environment. The extension of the decentralized and distributed Kalman filter to problems in decentralized control is described in [26, 27, 25, 24, 23]. It is shown how the model distribution results obtained for the decentralized Kalman filter lead to both the design of a controller and to the design of a control structure which is characteristic of the interconnections involved in the physical system to be controlled.

These ideas on control were implemented in the OxNav project aimed at demonstrating fully decentralised and modular mobile robot navigation and control. This was a particularly challenging project combining almost all aspects of the theory in a single demonstration system and requiring the physical realization of a mechanical and electrically modular system, and demonstrates more clearly than any other application the potential advantages to be gained from a decentralized approach to systems design. A modular vehicle consisting of a number of standardized modular cages was designed (Figure 5). Each cage contained a specific part of the overall vehicle function; drive unit, sensor, power distribution, communication systems [7, 8]. Each cage contained a processor, power and communication facilities, and all local software to implement the required decentralized functions of that unit. There is no central unit or processor where information is combined or where control is coordinated. A wide range of different vehicle systems were constructed from a small number of standardized cages, without the need to change either hardware or software. The decentralized control system for the vehicle demonstrated that the design of local decentralized control algorithms for an individual driven wheel unit allows the control of vehicles with any number of and kinematic configuration of driven and steered wheels. The decentralized navigation system is also described. The system employs a number of modular tracking sonar units. Each unit employs a model of vehicle motion to track environment features to provide independent estimates of vehicle location. The estimates are exchanged between sonar units to provide global navigation information. Vehicle guidance was achieved through exchange of information between vehicle drive units and sonar navigation sensors. The OxNav project won a number of major awards for innovation and industrial collaboration.

3.4 Organisation and Management

All early work on decentralized data fusion relied on the simple algebraic manipulation of a centralized estimation algorithm to obtain an equivalent decentralized estimator. The work by Manyika [19, 22, 21, 20] provided a completely different approach to the decentral-

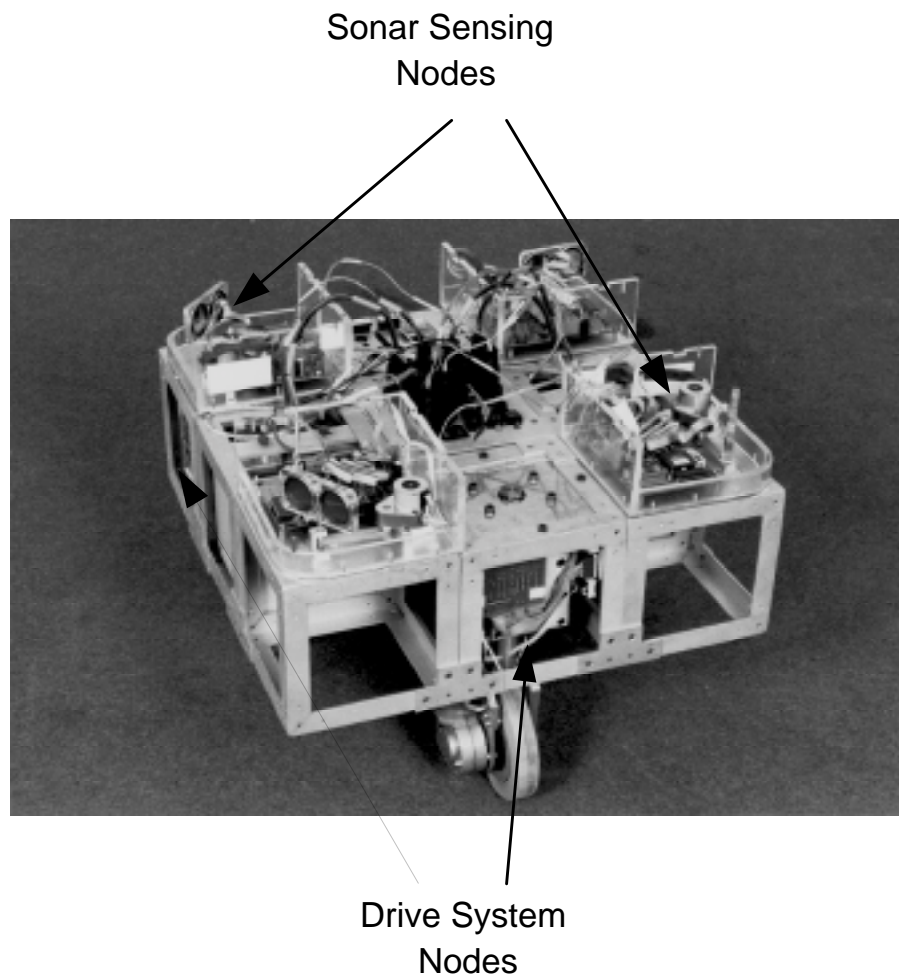


Figure 5: The OxNav Vehicle; a fully modular fully decentralised navigation and control system

ized data fusion problem based on an information-theoretic model of sensor observation and data assimilation. Information-theoretic models are much more fundamental to the data fusion problem than conventional state estimation techniques. In particular, the work demonstrated that all of the decentralized algorithms derived to this point can in fact be directly derived from information theoretic concepts once the problem has been defined through Bayes theorem in probabilistic form. It was also demonstrated that the quantities computed at sensor nodes in both the discrete and continuous filters may be described in terms of information quantities alone. Furthermore, the information-theoretic development of the problem demonstrates clearly why the decentralized filter is structurally and computationally a more natural formulation of the data fusion problem than is a conventional multi-sensor filter.

The information formulation of the decentralised data fusion problem was first demonstrated on the OxNav project; in particular for navigation and for sensor management.

Once the nature of decentralized sensing has been described in the form of information measures it became possible to quantify the value of a particular observation and the value of a sensor site within a sensing organization. If the value of an observation or site can be measured, then a number of additional questions may be asked of the sensing network. In particular, it becomes possible to address the problem of sensor management and network organization on the basis of information maximizing strategies. Sensor management addresses the problem of how individual sensor sites should act so as to maximize the amount of information available to the network.

The solution to the sensor management problem relies on the local measurement of mutual information gain resulting from a particular sensing action, and through the global maximization of this quantity by each individual sensor site. Sensor organization addresses the problem of what structure the sensing network should take under specific quantifiable system requirements. Given a probabilistic model for each sensor site and the observations made by each sensor, what network structure will provide, for example, the most robust system or the most informative system [17]. The solution to the sensor organization problem relies on a composite measure of the information generated by each node in the system, accounting for the possible connectivity between sensor sites and the local observability of different states at different nodes in the network.

The sensor management and organization problem demonstrate more clearly than any other aspect of the decentralized data fusion problem the value of using information-theoretic quantities to describe both individual sensors and the overall structure of the sensing network.

3.5 Tracking and Navigation

Decentralised methods have been applied to both tracking (picture compilation) and navigation problems.

With funding from Sowerby Research center, a fully decentralised picture compila-

tion simulator was developed [11]. The first, D0, simulator was written in Matlab. This provided a multi-target multi-sensor tracking simulator to demonstrate key ideas in decentralised data fusion methods, including; node filters, channel filters, and decentralised data association. The D1 simulator was written in parallel C for a Transputer network. The D1 simulator provided the same functionality as the D0 simulator but in the form of embedded code. A version of the D1 simulator was used to undertake research into communications management in decentralised systems [9]. The D0 simulator has also been superseded, the new version providing an easy to use graphical interface and improved structure. This simulator is intended as a good starting place for staff or students wanting to get a practical introduction to decentralised methods and algorithms. This new simulator can be accessed from the ANSER project web pages.

Work on decentralised navigation systems has taken a number of routes since the OxNav project. First has been the development of high-integrity, multi-loop navigation systems for autonomous land vehicles applications [6, 5, 28]. This allows comparison and fusion of results from multiple navigation loops in decentralised (information-theoretic) form. This decentralised structure is a substantial improvement over the oft-touted federated architecture. It provides a scalable method of building fault-tolerant multi-sensor navigation systems. These methods have now been applied on some large automated land vehicles in cargo handling and mining applications [37]. There has also been work, funded as part of the BA Systems RAFD project, on the development of low-cost hyper-redundant aided inertial systems incorporating decentralised and information-theoretic ideas [35, 36, 34]. These ideas are now being pursued in parallel with the ANSER project. Finally, there has been significant and important theoretical work undertaken in decentralised terrain navigation and SLAM algorithms [29]. These initial results indicate that the (decentralised) information form of the SLAM algorithm has many advantages over the state-space form, particularly when many platforms are involved in map building and map information needs to be exchanged.

4 The Technical goals of the ANSER Project

4.1 Objectives

The primary objective of the ANSER project is to demonstrate fully decentralised and modular picture compilation and terrain navigation on single and multiple flight platforms (UAVs). In turn, this will be used to demonstrate, in a highly relevant form to BA Systems operating divisions, how decentralised systems architectures result in:

1. Modular packaging of sensor and data fusion algorithms.
2. Scalability and on-line flexibility to addition of single and multiple sensors and flight systems.

3. Robustness and fault tolerance to failure in sensors, systems and platforms.
4. Providing a quantitative means of analysing systems performance issues such as communication and integrity.
5. Increasing degrees of controllability and autonomy in sensors and flight systems.

These objectives are being met by developing, from the outset, fully modular navigation and picture compilation instrumentation following the theoretical and practical principles developed in previous collaborative research projects. This specifies logical packaging of sensors with processors where possible, and explicit separation of functions such as observation pre-processing, data assimilation and inter-module communication.

4.2 Demonstrations

Fundamentally, ANSER is a demonstration project: The objective is to demonstrate functionality of decentralised data fusion theory and algorithms developed over the past 10 years in a form which is of direct relevance to BA Systems business units.



Figure 6: A UAV of the type developed for the ANSER project.

The ANSER project calls for the simultaneous deployment of up to four UAVs in decentralised configuration (see Figures 6 and 7). Four platforms are the minimum allowing demonstration of non-trivial decentralised communication policies. Each UAV is equipped with inertial, GPS and flight data sensors. Each UAV is also equipped with two payload sensors. The first payload sensor is always a passive vision system. The second payload is chosen from either a laser or a mm-wave radar. Both the laser and the radar

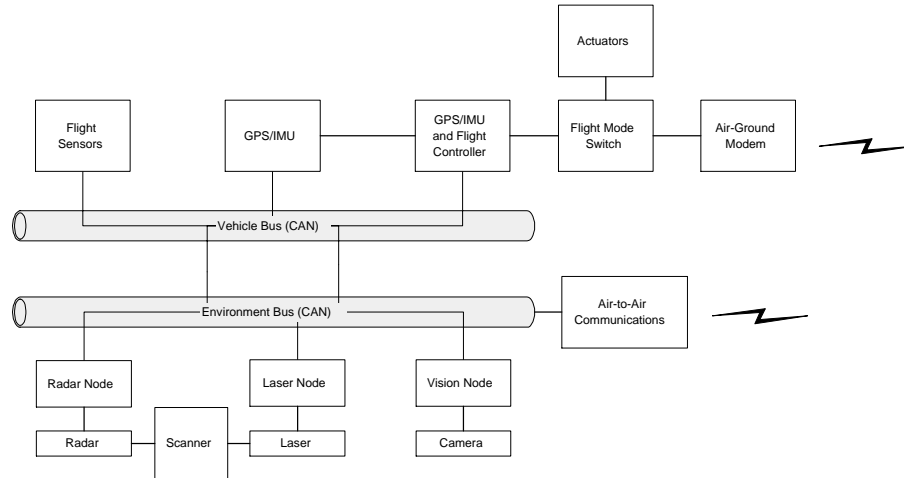


Figure 7: Functional architecture for the UAV. The internal structure provides a CAN bus for vehicle functions (flight critical), and a CAN bus for payload and map information. Each payload is fully modular and interchangeable.

are mechanically scanned using a common scanner design (see Functional Specification documents for further details). The UAVs are flown at the ACFR flight test facilities at Marulin, 175Km south of Sydney.

The UAVs will use the payloads to perform two primary functions:

1. Picture compilation: The detection and tracking of multiple ground targets given known locations (derived from GPS/IMU) for the flight platforms.
2. Simultaneous localisation and map-building (SLAM): The detection and tracking of multiple terrain features together with the simultaneous use of these in estimation of platform location, without independent knowledge of platform location (no GPS).

Each function will be developed and demonstrated in fully decentralised and modular form; across payloads on any one flight platform and across multiple payloads on multiple flight platforms. Figure 8 shows the structure of on-board algorithms.

The scenarios to be flown are aimed at demonstration of the key elements of the decentralised data fusion method. The scenarios can be broken down in to four main groups (see scenario definition documentation for details):

1. Single platform picture compilation: A single platform will be flown with multiple payloads in picture compilation mode. Demonstrations include the modular exchange of payloads (modularity, interoperability), and the in-flight failure and reconfiguration of payloads (survivability and flexibility).
2. Single platform SLAM: A single platform will be flown with multiple payloads in SLAM mode. Demonstrations include flight proving the SLAM method (not dis-

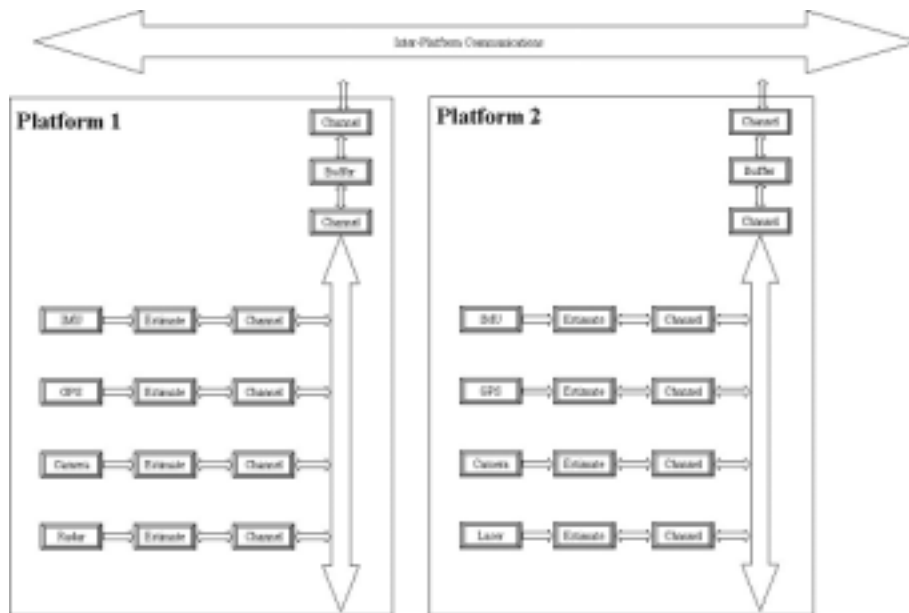


Figure 8: Algorithmic architecture for the UAV. Each payload operates an independent decentralised filter and corresponding channel filters for both picture compilation and SLAM modes. The internal function of each sensor node is hidden and their operation is transparent to the operation and location of other payloads.

cussed in this document), generation of terrain maps from decentralised payloads, with the same modularity and payload reconfiguration abilities as are demonstrated for picture compilation functions.

3. Multiple platform picture compilation: Multiple flight platforms will be flown with multiple payloads in picture compilation mode. Demonstrations will include the extension of function from one to four platforms (scalability), the transparent use of sensors on one platform by assimilation processes on other platforms (modularity, interoperability), reconfiguration of sensing due to failure of individual payloads, and task reconfiguration due to failure of complete flight platforms (survivability and flexibility).
4. Multiple platform SLAM: Multiple flight platforms will be flown in SLAM mode. Demonstrations will include the ability to share terrain maps between payloads on different flight platforms, to fuse maps from geographically separated payloads, and to demonstrate scalability and robustness of decentralised SLAM methods.

The scenarios form a logical progression for the implementation of the theory and demonstration of algorithms.

4.3 Research

The ANSER project is focused on demonstration of existing theory. However, the complexity of the demonstrator still requires research in three main areas:

1. The extension of theory and methods to airborne scenarios: There is a necessary process of mapping a general theory and set of methods to this specific, and demanding, application. Most previous work undertaken in decentralised methods has been done on ground-based sensors or land vehicles. An air scenario has more degrees of freedom, faster data rates, and larger demands on processing and communication management.
2. The development of sensing, terrain data acquisition, and terrain or target representation methods: The development and packaging of payload sensors for airborne application has been a significant issue; particularly weight, volume and data acquisition speed. The extraction of appropriate terrain features for picture compilation and SLAM, the modeling and communication of these between different payloads has also been an area of significant study.
3. The development of decentralised and information-theoretic SLAM methods: One significant theoretical advance made in this project is the development of a decentralised formulation of the map building and SLAM problem. This has required the re-formulation of map building equations in information-theoretic form and the study of how maps from different platforms can be exchanged and assimilated.

ANSER has also provoked a number of new research areas, beyond the scope of the current project, but of considerable future value in decentralised systems. These are discussed in section 5.

5 Beyond ANSER

ANSER is mainly concerned with the development, implementation and demonstration of decentralised estimation and data fusion methods. However, as described in section 3, decentralised methods also encompass ideas in information-theoretic systems modeling, sensor and system management, and decentralised control. While the current ANSER project is concerned with core decentralised data fusion methods, the future focus will be on more widely applicable theories of information based decentralised systems.

ACFR staff and students are engaged in three substantial areas of research related to the future of decentralised systems: i) modeling systems of systems; ii) Decentralised control; and iii) extension of decentralised methods to large-scale ground-based systems (Argus).

5.1 Modeling Systems of Systems

Decentralised, and more generally, information-theoretic methods, offer a uniquely powerful method of mathematically modeling large-scale systems of systems.

Decentralised methods allow information gathering and decision making systems to be described in a mathematically rigorous and modular manner. Decentralised methods provide three essential ingredients necessary to develop a usable ‘theory’ for systems of systems:

- **Analytic:** Decentralised and information-theoretic methods provide an ability to analyse and reason about a system and it’s information gathering or decision making role. In particular, the process of local information formation, communication and assimilation, and decision making are well formulated.
- **Composable:** Decentralised methods also provide a compelling ability to compose mathematical descriptions of larger systems from descriptions of component sub-systems. Significantly this is a consequence of the inherent modularity and scalability of decentralised system algorithms.
- **Predictive:** Information theoretic methods provide a natural and powerful ability to reason about composite systems and in particular to study, *a priori*, system pay-offs.

Work on this ‘systems of systems’ theory is a particular focus of current research at the ACFR as it impacts both on ANSER and on other, civilian, projects on which the Centre works.

5.2 Decentralised Control

Decentralised decision making and control is a logical extension of decentralised and information-theoretic modeling. Once information is made available locally, in a decentralised form, and controller objective functions have been defined, then it is possible to decentralise standard control laws in much the same way that standard data fusion algorithms are decentralised.

Two examples of decentralised control are the decentralised sensor management methods described in [22] and the decentralised LQG controller for the modular OxNav vehicle described in [27]. The sensor management methods are concerned with discrete decisions about allocation of sensors to targets; target cuing and hand-off (control for target tracking, once an assignment has been made, is handled locally). Conversely, the decentralised LQG controllers are concerned with continuous variables such as steer angle and wheel velocity. The sensor management methods are defined in a fundamental manner, in terms of decision theory; using information measures, decision utility and outcomes in a formal manner. Conversely, the decentralised LQG controller method is the result of algebraic manipulation of conventional state-based LQG controllers.

The goal of a decentralised control algorithm is to exert coordinated control between a scalable number of sensors and platforms, through the exchange of information and local decisions, and without the need for a central arbiter. For example, in a multiple-platform surveillance task, for each sensor and platform to make its own decision about where and what to sense, and by coordinating these decisions with other sensors and platforms, to arrive at a globally-optimal control for the system as a whole. Further, in the event of failure of one or more sensors and platforms, to be able to reconfigure the control of all sensors and platforms.

The control problem for systems such as ANSER is hybrid, involving both the discrete allocation of resources and continuous control of trajectories. For this reason, the information-theoretic methods developed for sensor management offer the best approach to developing decentralised control algorithms because of their underlying basis in information and decision theory. This is the approach currently being pursued at the ACFR by students and staff. Three areas are under investigation; the establishment of mission profiles, for tasks such as area surveillance, target location and engagement, and map building. These involve the establishment of information metrics for tasks, and the development of decision methods allowing the exchange and comparison of utilities between different sensors and platforms. While there is a significant amount of new theory to be developed, the approach offers the possibility of very high degrees of autonomy in individual platforms and high degrees of survivability in overall systems. It is intended to undertake demonstrations of these ideas on the ANSER simulator.

5.3 Large Scale Systems

Work is also underway at Sydney to develop a ground-based sensor network to be located at the Marulin test site¹. The aim of this work is to demonstrate large-scale scalability of decentralised data fusion methods and to show distribution across both air and land environments. For historical reasons, this is called the Argus project.

Currently the project is developing a group of ground-based sensor nodes, based on the same architecture as the ANSER project. The nodes include vision, and multi-spectral cameras, lasers and (in the future) radars. Sensor nodes are being physically constructed in a modular fashion around a PC104 architecture and linked by radio ethernet. A major advantage of this development is that it is not constrained by weight and size as are the payloads for the ANSER project; this considerably simplifies development.

The Argus network will be used for both air-target tracking and hand-off of ground targets from air to land sensors. The practical objectives are to demonstrate the applicability of decentralised methods to a broader range of data fusion problems, and to serve as the primary test-vehicle for system-of-system theories and algorithms.

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