

A vision of network-centric ISTAR and the resulting challenges^{*}

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ABSTRACT

The well understood lack of a ‘silver bullet’ sensor technology which can provide everything wanted from Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) when using a single sensor type on a single platform, combined with the improved ability to network multiple platforms together is at the heart of the growth in network-centric ISTAR. When this is linked to the growth in data storage capacity then a much richer and more beneficial opportunity for the transformation of network-centric ISTAR opens out. In particular the long term storage of sensor data (at detection or pre-detection points in the sensor processing chain) enables the traditional one-way data fusion (or signal processing) approach to be turned into a much richer two-way (or bi-directional) chain of adaptive processes where higher level context is used routinely, hypothesis testing is the norm and the system can report on both the positive presence and absence of ‘targets’ of interest.

Finally the paper discusses some of the key challenges to be overcome if the potential advantages of fully networked bi-directional adaptive signal and data processing are to be realised.

Keywords: network, net-centric, ISTAR, intelligence, surveillance, target acquisition, reconnaissance, signal processing, data storage, information processing, fusion, transformation

1. INTRODUCTION

Making the most of the sensors available to military forces is a constant challenge, and involves research and development activities focused on sensors, data/information fusion, networking, automation, system management and a host of other activities. This paper is focused on the coming transformation in how signal and data processing is conducted immediately behind the sensor.

I begin by discussing two main trends: one is the impact of improved data storage and processing power on the signal and data processing chain (in section 2); the other is the impact of increased sensor networking (in section 3). This discussion covers the reason for these trends and the benefits of opportunity to transform signal and data processing.

There are many challenges to be overcome if the potential advantages are to be achieved, and I discuss several of these in section 4. Also in section 4, I make reference to where current research within the joint UK and US International Technology Alliance (ITA) in Network and Information Science (NIS) is starting to address these challenges.

1.1 Caveat: a personal view

The paper presents my personal views and as such does not necessarily represent the views of the UK Ministry of Defence or of any other government body mentioned in this paper.

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1.2 Signal and Data Processing

There is no one commonly agreed and used set of terms and relationships within the area of data and information ‘fusion’; though there are some commonly used constructs. Thus, it is worth starting by setting out what I mean when discussing signal and data processing.

When considering the entire chain from the receiving of a signal (of some kind) at a sensor (of some kind) to the derivation of intelligence[†] then this can be broadly broken down into the following three step chain:

- a) signal processing transforms the signal received by a sensor into data;
- b) data processing transforms output from the signal processing into information (e.g. a typical tactical picture);
- c) information & intelligence processing transforms information into intelligence.

In this broad partition of the chain into three steps the term information is used to represent the half way point between transforming received data into intelligence; thus it does not match the definition in [1] in which information is defined as ‘unprocessed data of every description which may be used in the production of intelligence’, nor necessarily an information theoretic or human factors based definition. Instead, it is closer to a definition of the form ‘data presented in a form and with supporting context such that it is meaningful to a person’.

Within this broad three step chain, the area that I have concentrated on in this paper is the first two steps and they can be expanded into a richer or more detailed chain of processes as shown in Figure 1 [2].

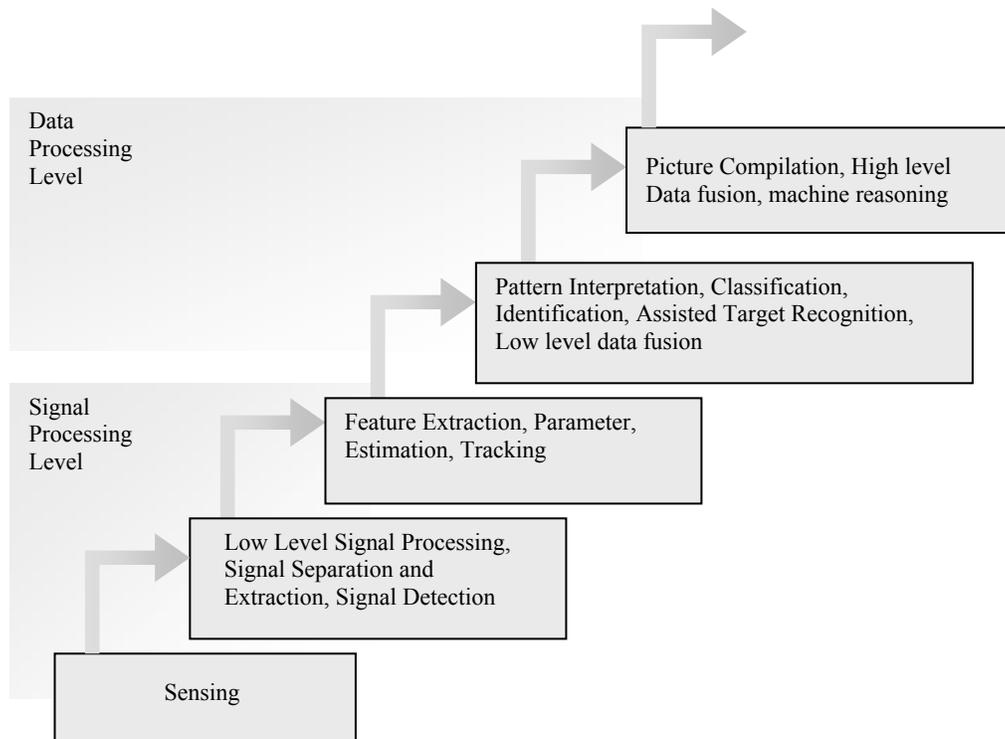


Figure 1: Signal and Data Processing Chain

The signal processing steps in the chain in Figure 1 must be able to process data at the speed at which it arrives, and provide a near-real time output. Therefore, the design of signal processing chains has been fundamentally influenced by the generally very limited data storage and processing power available at the time they were designed.

[†] Intelligence is ‘the product resulting from the processing of information concerning foreign nations, hostile or potentially hostile forces or elements, or areas of actual or potential operations’ [1].

To generalise, a typical signal processing chain is designed as a one way process (as is implied by the arrows in Figure 1) which works as a series of steps where data is only stored at each step for a limited amount of time, and a which processing power is such that each step provides a pre-determined output to the next step. Thus, for example, a typical moving target radar system will have one process which extracts plots from a scan (and the pre-plot memory is then filled with the next scan), then a second process which converts plots to tracks (and the plot memory is then filled with the next set of plots), and the output is a set of tracks.

The rapid growth in both data storage capacity and processing power means this fundamental limitation can be removed. The impact of this is discussed in Section 2.

1.3 Networking sensor systems

The lack of a ‘silver bullet’ sensor technology which is able to provide everything wanted from a single sensor means there are many different types of sensor systems exploiting a wide range of phenomena and modalities. Thus we have many different types of radar sensors, imaging sensors operating at many different spectral bands, vibration sensors (inc. seismic and acoustic), etc.

Therefore, most Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) tasks require for their successful execution the use of a set of sensor systems which are used together as they have a synergistic relationship (or to put it another way they can compensate for each others weaknesses) and together they provide an improved output or ‘product’. Exploiting the synergy of a set of sensor systems working together is why such systems are ‘networked’ together. Such networks are usually not limited to just sensors but extend out into the command and control systems. Experience with such networks (e.g. JTIDS/Link 16) has underpinned the development of the concept of Network Centric Warfare (NCW), Network Enable Capability (NEC) and Net Centric Operations (NCO) [3].

As networking technology has developed then such networks have grown in their sophistication and ubiquity. In World War II there were a number of well developed air defence sensor networks, but these were much less sophisticated and ubiquitous than current air defence sensor networks such as those exploiting modern data link technologies (e.g. JTIDS/Link 16 or the Co-operative Engagement Capability (CEC)).

There continues to be rapid development in the technologies which enable networking of sensor systems, and thus (as it continues to deliver benefits) there will be a continued growth in both the ubiquity of networking, and in the depth of such networking. Section 3 discusses the impact of these.

1.4 Network & Information Science (NIS) International Technology Alliance (ITA)

As noted above, the resulting challenges are discussed in section 4 together with where research within the NIS ITA is beginning to address the challenges.

The NIS ITA was a landmark collaboration established by the UK Ministry of Defence (MoD) and the US Army Research Laboratory (ARL) in 2006. The ITA comprises both government (MoD and ARL) as well a consortium of 15 academic institutions and 8 industrial companies in the UK and US. The ITA conducts collaborative research focused on four technical areas. These are (i) Network Theory, (ii) Security Across a System of Systems, (iii) Sensor Information Processing and Delivery, and (iv) Distributed Coalition Planning and Decision Making. Therefore, the objective of the research is to provide the fundamental underpinnings for enhanced Network Centric Operations across a wide range of operational contexts and jointly across the physical, social and cognitive domains. Further information of the ITA research programme and its members can be found at <http://www.ususkita.org> [4].

2. THE BI-DIRECTIONAL SIGNAL PROCESSING CHAIN *enabling adaptive, context aware signal processing*

As outlined in sub-section 1.1, the basic design of the signal and data processing chain assumes:

- (a) a one-way flow of data between processes;
- (b) only short term data storage at each process (typically in a radar no longer than a single scan) ;
- (c) an objective of producing a single (or small set) of pre-determined products (e.g. a radar providing tracks on moving targets or a video camera providing motion imagery).

This was due to the need for signal and data processing systems to operate in real-time (as they must keep up with the arrival rate of signals at the sensor receiver) and historically technology could only provide limited data storage and processing power.

2.1 The basic design of a bi-directional signal processing chain

The continued rapid growth in data storage capacity and processing power, as captured in statements such as Moore's Law, means that this basic design assumption can be changed to one in which:

- (a) data is stored for a significant period of time (at earlier and earlier points in the signal processing chain);
- (b) data can be processed and re-processed as required.

The re-processing of data as required introduces two further changes to the basic design approach. These are:

- (c) a two-way or bi-directional flow of data between processes;
- (d) the ability to provide a range of different products on demand.

Thus the change is from a one-way chain in which data is stored for a very limited period of time at each processing stage along the chain and the system is designed to produce a single product to a bi-directional chain with significant storage of data at, at least, one processing stage along the chain and with an approach to re-processing data as required to provide a range of products.

2.2 Why change: example benefits

Just because we can change the basic approach to the design of the signal processing chain does not necessarily mean we should. The only reason to change is if there are significant benefits to be had; they may be performance, future proofing, supportability or cost benefits. Therefore, this sub-section discusses two example sensors: a moving target radar and a video camera.

As noted in section 1.1, a typical moving target radar system will have one process (or set of processes) which extracts plots from a scan (and the pre-plot memory is then filled with the next scan), then a second process which converts plots to tracks (and the plot memory is then filled with the next set of plots), and the output is a set of tracks. In this case there are a number of obvious potential benefits which can be obtained from a bi-directional signal processing chain with the associated long term storage of data.

First, as is already done in some radar systems, the existence of a track can be used to predict where the next plot which would associate with the track will be 'seen' and, if necessary, a lower than normal confidence plot might be accepted. For example, if the normal threshold required by the plot extraction process to declare a plot is the 'detection' of the object in 3 out of 4 radar bursts then it might be acceptable to reduce this detection in 1 or 2 out of the 4 bursts. This would (and does) improve the ability to maintain a track when the signal to noise ratio drops for a short time or the target is eclipsed. Secondly, as again is already done in some radar systems, the transmitted waveform can be specifically chosen based on previously known target motion inferred from an existing track in order to improve the probability of detection. Thirdly, and moving beyond current systems, if another sensor on the same platform detects a target at a particular point or along a particular line of bearing where no radar track has been reported then the radar data can be re-processed to 'see' if there were any low confidence plots or tracks which match the other sensor report in time and space.

Clearly, as effectively admitted above, it is an over simplification (and indeed incorrect) to state that currently all signal processing chains are one-way systems. Many do involve some form of feedback loop. However, they are not fundamentally envisaged as bi-directional chains with long term data storage (possibly at several or changing points in the processing chain over the lifetime of the sensor) and the ability to re-process data on demand.

Turning now to another type of sensor, specifically to video cameras: these are very interesting sensors as they are becoming much more prevalent and can be (though are not yet routinely) used to provide many different products. Thus they provide a classic example of the ability to collect sensor data once and then use it for many purposes. A video camera can provide at least 9 different products after suitable re-processing, including:

- (a) Full motion video;
- (b) Reduced frames per second for general awareness;
- (c) Super-resolved image of an object;
- (d) Mosaic image;
- (e) Thumbnails at significant change points;
- (f) Moving target indication;
- (g) Longer term change detection;
- (h) Processed to identify (local) weather (e.g. fog, rain, high winds);
- (i) 2/3D representation of static objects.

The above ignores the ability to play with other factors such as colour balances or polarisation, or any number of target and function focused methods of compressing the imagery. In summary, video cameras lend themselves to a future in which the local (to the sensor) re-processing of previously gathered and locally stored sensor data is normal.

2.3 General benefits

The above examples have concentrated on simple and specific examples of benefit. However, they have included some specific examples of a number of more general benefits available for such a bi-directional processing chain incorporating significant data storage. These include:

- (i) Hypothesis testing (i.e. the ability of the sensor processing chain to better support the testing of hypotheses by re-processing the available data from a number of sensors to test the hypotheses);
- (ii) Higher level context information is routinely used to inform lower level processes;
- (iii) A sensor can easily be exploited for multiple uses (i.e. can provide multiple products);
- (iv) A sensor system can report on both the positive presence and absence of 'targets' of interest.

The last of these: the ability to provide positive confirmation of 'target' absence is one which currently almost all sensor systems are not designed to do. Instead, it is left to the human operator or receiver of the sensor product to use their knowledge of the sensor's performance to infer from the absence of any reported 'targets' what the likelihood is that there are actually no 'targets' in a particular area. This becomes progressively harder the further a consumer of sensor product is from the sensors, as there is also a general lack of reporting of which areas have been 'viewed' by sensors. Therefore, actively being able to query the system to get a positive confirmation of absence would be extremely valuable: in other words, the sensor system would be able to provide a commander with a clear view of where the enemy is not present, and where there is no information on presence or absence, as well as the traditional view on where the enemy is.

Therefore a bi-directional processing chain incorporating significant data storage enables adaptive, context aware signal and data processing, which has a number of significant benefits.

3. NETWORKING

Section 1.2 outlined how sensors systems are increasingly being networked together, as (in general) the product of more than one sensor system is required to undertake any ISTAR task and there are synergistic benefits to be obtained from the networking of sensor systems. Indeed the networking of sensor systems, with other systems, is fundamental to the concept of NCW, NEC and NCO [3].

3.1 General benefits of sensor system networking

There are, it can be argued, two main reasons why sensor systems are networked together. These are:

- (i) Exploiting significant differences between sensors, and thus typically enabling a scan-cue-focus method of operation in which one sensor will cue another to 'look' more closely at an area;
- (ii) Exploiting the spatial separation of two similar sensors, and thus typically enabling a particular product to be improved (e.g. completeness of a radar track).

Individually and in combination these two are exploited to improve the quality, quantity, timeliness and/or confidence of the product generated by the networked sensor systems. When linked to command and control systems/assets then the improved performance obtained is fundamental to the concepts of NCW, NEC and NCO [3, 5, 6]. This has led to a growing ubiquity in the networking, and plans for the networking, of sensor systems.

3.2 Depth of sensor system networking

The bandwidth available from both point-to-point and broadcast communication technologies, which are used to underpin the networking of sensor systems, have grown over time and are set to continue to grow. This has enabled an increase in the depth of networking: thus, for example, the track based air picture passed over JTIDS/Link 16 is based on selecting the 'best' track from the set of tracks produced by the sensor systems contributing to the network while in the CEC a track is produced from a set of plots contributed by the sensor systems. In other words, CEC which is more recent than JTIDS/Link 16 works by integration of data at an earlier stage within the signal and data processing chain set out in Figure 1. The trend is that future networking of sensor systems will result in the horizontal linkage between the systems (and thus the data sharing between them) occurring at earlier stages within the signal and data processing chain.

3.3 Agile mission groups and networks of networks

As networked sensor systems become more ubiquitous there will be an increased opportunity and need to, and benefit from networking such networks together, in particular when forming agile mission groups or agile groupings [5, 6].

As a thought experiment, let us hypothesise a future operation is underway in some part of the world. A network of wide area search ISTAR assets has been deployed to provide broad coverage of the entire theatre; this theatre ISTAR network is linked together, generally works in a scan-cue-focus manner and has a mission set which involves a list of key high priority targets such as major enemy C2 nodes and strategic assets. Within a particular region of the theatre there is a divisional (or perhaps brigade or corps) level ISTAR network, again with its priority targets. Also operating in this region are a number of ground formations, within which there are local mobile networks. Operating in the region or transiting through it is a 4-ship of fast jet combat aircraft and a pair of stealthy Uninhabited Combat Air Vehicles (UCAVs), with their own intra-flight links forming another network. This set of networks is illustrated in Figure 2.

Figure 2 shows some form of generic link between elements of the individual networks. The ability of this network to transfer all of the received signals (or resulting data) from each node to either a central node or to certain key nodes for central processing will depend on the ratio of the rate of the received signals (or resulting data) to communications bandwidth. In certain cases, it may be possible to pass all or a large fraction of the data around the network, but this is likely to only work for highly specialised point-to-point networks using very high data rate links (e.g. laser communications). In the majority of cases, it is more likely that much data will need to be stored locally (as illustrated in Figure 2) and this data will only be able to be uploaded to some form of central long term storage when the systems 'dock' with an element of fixed infrastructure (i.e. link up with the wired world). Therefore, the 'edge' of the network

will be routinely the place at which the vast majority of recent data is stored and at which the richest current picture exists[‡].

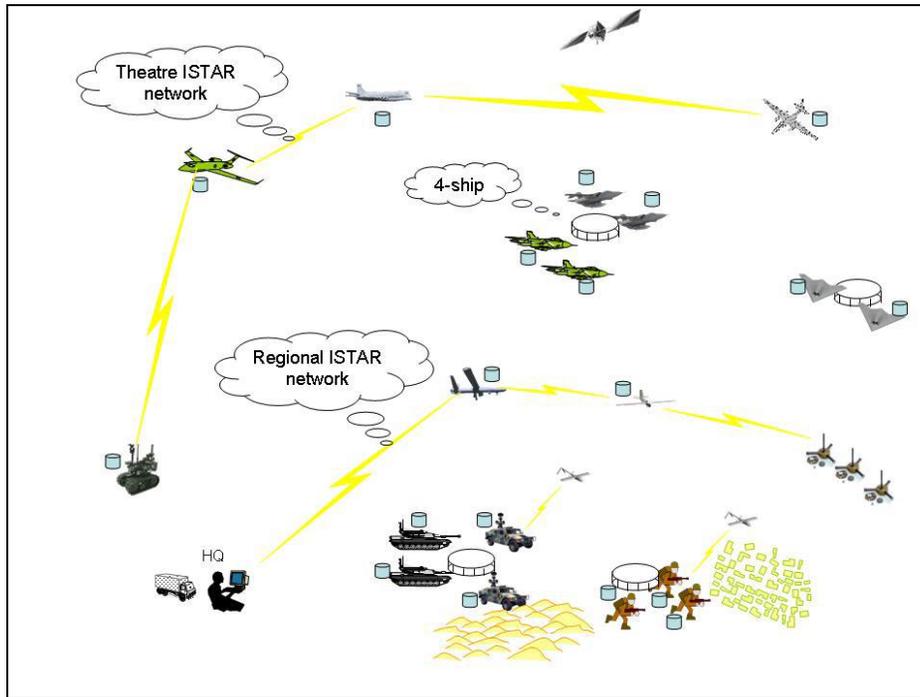


Figure 2: Illustrative network of sensor networks

The networks illustrated in Figure 2 could operate in splendid isolation from each other, but as they overlap in terms of their Areas of Interest (AoI) there is clearly benefit to be obtained from them acting synergistically by, at least, providing a record of ‘detections’ of items of interest to each other: naturally the first step is the exchange of a list of items of interest between the networks. However, it is inevitable that at certain times and in certain places the individual networks will have problems prosecuting particular targets, while at other times and places they will have unused resources. Therefore, it is also inevitable that by sharing their resources and exploiting the synergies between the different networks that they could, if operating as a single joined up network provide a better product than they could if they merely cued each other.

3.4 The vision of net centric ISTAR

Therefore the vision is of a network of sensor networks acting as a near optimum synergistic whole in support of agile grouping which combines:

- (i) the advantages of networking in terms of synchronisation in space, time and collection mode,
- (ii) the trend towards increasing the depth within the signal and data processing chain at which such networking occurs,
- (iii) with a bi-directional signal and data processing chain (supporting adaptive, context aware signal processing),

to enable the detection of currently undetected targets, to achieve the required levels of discrimination between targets, support achieving the general benefits discussed in sub-section 2.3 and thus improve the quality, quantity, timeliness and/or confidence of the product [2].

[‡] In many ways this is not a new phenomenon. Instead it has long been the case that for Armies the lower tactical levels have a much richer picture of the local environment than higher command, and only a fraction of the information available at these lowest levels is ever passed up the reporting chain. But careful organisation of the reporting chain, including the briefing of command intent (etc), is aimed at (and often succeeds in) ensuring that what is reported, over a usually bi-directional link, is highly relevant and useful.

4. CHALLENGES

Clearly there are many challenges to be overcome to achieve the vision, and the potential benefits, outlined above in sub-section 3.4. The objective of this section is to discuss some of them, and identify where research within the NIS ITA is beginning to address them. The aim is not to try to discuss all the challenges as these will occur in many different domains (including the physical, social, cognitive, programmatic and acquisition domains) along the road to the vision. Instead the objective is to highlight a number of the key fundamental challenges where research is required.

The challenges I have chosen to discuss are:

- (a) understanding the trade-off between benefits and costs;
- (b) adaptive, context aware signal processing algorithms;
- (c) data push and pull within such a system-of-systems;
- (d) designing such a system-of-systems as an 'open' system of loosely coupled elements;
- (e) discovering, joining and leaving the network of sensor networks
- (f) positive reporting of absence;
- (g) managing such a system-of-systems.

4.1 The trade-off between benefits and costs

If such a vision is to be implemented then that will require either a bold leap of faith, or some methods of addressing the extent to which it should be implemented and the exact method of implementation. This requires an ability to understand benefits and costs.

This discussion focuses on benefits and one particular area of benefit: namely, the ability to quantify the improvement in the product of such sensor system networks. As noted above, improvements in the product are likely to be in terms of quality, quantity, timeliness and confidence. However, such metrics can be applied at the various different stages within the chain from the receiving of a signal at a sensor to the derivation of intelligence: therefore, there is a need for an agreed and useful set of metrics [2].

The ITA is addressing the fundamental issues of how to specify and develop a framework of such metrics. This is being done as part of a project which is focused on and titled the 'Quality of Information (QoI) of Sensor Data'. QoI is used to represent the need to understand such metrics and it is recognised that QoI has different meanings and attributes depending on the context and application [7, 8]

4.2 Adaptive, context aware signal processing algorithms

Clearly exploiting the benefits enabled by designing the signal and data processing chain as a bi-directional chain incorporating significant data storage requires the development of suitable adaptive, context aware signal processing algorithms. As discussed in sub-section 2.2 there have already been implemented a number of adaptive, context aware signal processing algorithms. However, such approaches are still rare and there is a need for continued development within this area [2].

The NIS ITA has a task within a project titled 'complexity management of sensor data infrastructure' which is aimed at extending traditional signal processing by incorporating context, trust and risk within a semantically-mediated framework [7, 8, 9, 10].

4.3 Data push and pull within such a system-of-systems

A bi-directional processing chain by definition involves the two way flow of data. This introduces the interesting question of when to 'push' what data to the sensor system to enable it to most effectively process the data it has stored locally (or how to enable it to 'pull', possibly via subscription based smart push/pull approaches, the data from elsewhere to enable it most effectively to carry out the tasks it has been given).

In the limit the answer to the balance of push and pull might involve an understanding of the overall effectiveness and efficiency of using a variety of communications links to move data to the ideal processing point (based on an understanding of the trade-off between the 'costs' of using a communication link to pass data versus a processing resource).

4.4 An 'open' system of loosely coupled elements

Such a system-of-systems will not be a single monolithic entity purchased and introduced into service as a single 'big bang'. Instead, it will 'grow' and change over time as technology develops and systems enter service, are updated and leave service. Therefore, it would be highly advantageous to be able to design such a system as an 'open' system of loosely couple elements where only the interfaces are specified.

This is clearly a significant challenge for the vision outlined above. It would be simpler to achieve if each sensor could be treated as a single element, within which the point at which data is stored and at which re-processing of data occurs could change over time. This idea is not in direct conflict with the idea of a bi-directional design (though it would not be simple as is clear from the discussion of 'push' and 'pull'). However, a major complication is introduced by the changing depth at which networking may occur, as if co-operation is to occur between sensor systems at points within the signal processing chain then there are many more interface points and they may change over time.

It is likely that some of the NIS ITA research within the 'complexity management of sensor data infrastructure' project into an agile Service Orientated Architecture (SOA) and on treating an ISR network as a distributed database will be relevant to this challenge, and the previous challenge.

4.5 Discovering, joining and leaving such networks of sensor networks

There are clearly a number of challenges associated with how such networks of sensor networks would discover, join and break apart again. Possibly the two most major challenges in this area are closely related and are (i) how this could happen in a secure manner, and (ii) how to do this within a coalition.

Within the NIS ITA there are three projects dealing with security across a system of systems [4, 7, 8]. One of these projects is focused on the issue of how to formally specify and implement a set of security policies (which has clear application, and can be extended into the role of formal policy specification and implementation in areas other than security). The other two are equally applicable as they address 'Energy Efficient Security Architectures and Infrastructures' and 'Trust and Risk Management in Dynamic Coalition Environments'. There is another relevant project on the 'Interoperability of Wireless Networks and Systems'.

4.6 Positive reporting of absence

As discussed above in sub-section 2.3, such a system-of-systems should be able to undertake two tasks which are not supported by current sensor systems: these are hypothesis testing and positive reporting of the absence of 'targets' of interest in an area.

Hypothesis testing is, conceptually, relatively simple to support using such a system-of-systems though the actual implementation would require the development of suitable approaches and reasoning methods. The positive reporting of absence is perhaps equally conceptually simple, but it has the added challenge that it is not as simple as applying the same approach as it used for the positive confirmation of the presence of targets as it is fundamentally concerned with attempting to prove the negative: that this is hard to do is the reason the legal system is based upon proving that a person committed a crime, rather than having the person have to attempt to prove that they did not commit a crime.

4.7 Managing such a system-of-systems

There are two key issues which make the management of such a system-of-systems so challenging. The first is that elements of such a system-of-systems will consist of machine-to-machine networks operating at rates which are too fast

to allow direct human authorisation of all the decisions: indeed such networks already exist. The second is that each sensor network within the network has a different master with a different mission, and if they are to come together into a single delivery network (to make best use of the sum of their available resources and the synergies between them) then we have to deal with how to set priorities and objectives across a dynamic set of missions (each of which is subject to sudden and unexpected change).

The above complexity is likely to lead to networks of sensor networks which have emergent properties and thus the position of the human in managing the behaviour of such a network, and what tools would be required, is unclear.

The ITA has a project titled 'task-orientated deployment of sensor data infrastructures' which is addressing a range of issues related to this challenge including resource allocation across multiple dynamic missions, and as this progresses it is likely to undertake the fundamental research required to tackle this core challenge to achieving the vision [7, 8, 11, 12].

5. SUMMARY

This paper has presented the rationale for adopting a basic approach to the design of signal and data processing chains which assumes and enables a bi-directional flow between processes and incorporates significant local storage. It has described the broad synergies between this design approach and improved networking of sensor systems (including both the ubiquity of such networking and the depth at which it occurs). These two strands are then combined into a vision of the future in which a network of sensor networks acts as a near optimum synergistic single sensor system in support of multiple dynamic agile groupings at the same time. Finally, a set of key challenges which need to be overcome if this vision is to be achieved are set out and discussed.

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REFERENCES

- [1] AAP-6 (2007) NATO glossary of terms and definitions
- [2] Defence Technology Strategy 2006, UK Ministry of Defence, Oct 2006
- [3] Alberts, D.S., Garstka, J.J., Hayes, R.E. and Signori, D.A., "Understanding Information Age Warfare" CCRP, ISBN 1-893723-04-6 (Aug 2001)
- [4] Cirincione, G. and Gowens, J., "The International Technology Alliance in Network and Information Sciences," IEEE Communications Magazine, pp. 14-18, March 2007
- [5] Capability Manager (Information Superiority). 'Network Enabled Capability: an introduction', UK Ministry of Defence, version 1.1, April 2004
- [6] 'Network Enabled Capability handbook' JSP 777 Edn 1, UK Ministry of Defence
- [7] Pham, T. and Pearson, G. 'US-UK ITA Sensor Information Processing and Delivery' NATO SET-130 RSY-23, Paper NBR-1, Mar 08
- [8] Pearson, G. and Pham, T. 'The challenge of sensor information processing and delivery within network and information science research' SPIE Defense & Security Symposium: Defense Transformation and Net-Centric Systems 2008, Orlando, FL, March 2008
- [9] Guo, B., Wang, Y., Smart, P., Shadbolt, N., Nixon, M., and Damarla, T., "Approaching Semantically-Mediated Acoustic Data Fusion," IEEE MILCOM, Orlando, FL, November 2007.
- [10] Nixon, M. and Carter, J. "Automatic Recognition by Gait," Proceedings of the IEEE, 94 (11). pp. 2013-2024. ISSN 0018-9219
- [11] Rowaihy, H., Johnson, M.P., Eswaran, S., Verma, D., Bar Noy, A., Brown, T., and La Porta, T., "A Survey of Sensor Selection Schemes in Wireless Sensor Networks," SPIE Defense & Security Symposium: Unattended Ground, Sea, and Air Sensor Technologies and Applications IX, Orlando, FL, April 2007.

[12] Preece, A., Gomez, M., de Mel, G., Vasconcelos, W., Sleeman, D., Colley, S., Pearson, G. and La Porta, T., "Matching sensors to missions using a knowledge-based approach," SPIE Defense & Security Symposium: Defense Transformation and Net-Centric Systems Conference, Orlando, FL, March 2008.