Sensor-Mission Assignment: A Scenario-Driven Walkthrough

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***Abstract*—This paper attempts to provide an end-to-end walkthrough of sensor-mission assignment techniques being developed in ITA Project 8, starting with information requirements, and ending with delivery of actionable information and intelligence. The walkthrough is situated within scenarios currently under development in TA3 and TA4. The paper has two aims: (1) to facilitate integration of P8 approaches, together with aspects of P9 and P12; (2) to align the P8 work with wider activities that use the TA3 and TA4 scenarios. The paper concludes with a list of open questions and issues.**

I. Introduction

In ITA Project 8, *Task-oriented deployment of sensor data infrastructures*, we are developing a suite of techniques to tackle the sensor-mission assignment problem; these approaches are ultimately intended to fit together to provide an end-to-end solution. To guide this work, we recently proposed an overall architecture [1]. This paper aims to take us closer to our goal by performing a walkthrough of the P8 techniques in the context of a particular scenario. The primary purpose of the walkthrough is to check if everything fits together, and to reveal any discontinuities or incompatibilities. Once any problems are resolved, it is hoped that the walkthrough can form the basis of an end-to-end demonstration in the future.

The walkthrough has a secondary purpose: to situate the P8 work in the context of scenarios currently under development in ITA TA3 and TA4. By so doing, our work will become aligned with other approaches situated in the same contexts, making it easier to compare and connect work across the ITA. The walkthrough is designed to be compatible with two scenarios:

- the TA3 "border site" scenario[1] involving, among other things, protection of a main supply route (MSR) which is under threat by insurgents [2], and
- the TA4 "humanitarian intervention" scenario[2] involving, among other things, a road in an earthquake-hit region that is of great tactical significance to insurgent forces [3].

For the purposes of the walkthrough, we conflated the TA3 MSR and TA4 road into the same location, allowing us potentially to demonstrate capability in both TAs. Throughout the document we will simply refer to the location as the MSR (Figure 1[3]).

Fig. 1. The main supply route (MSR)

II. Overview of Our Approach and Architecture

In the context of ITA Project 8, the problem of *sensor-mission assignment* is defined as that of allocating a collection of intelligence, surveillance, and reconnaissance (ISR) assets (including sensors and sensor platforms) to one or more missions in an attempt to satisfy the information requirements (IRs) of the various tasks comprising the missions. IRs will be identified as part of the process of mission planning [4]. For example, the mission to protect the MSR would involve, among other IRs, the requirement to detect suspicious activity on the road. Logistically, the coalition carrying out the mission(s) will have a set of available ISR assets (platforms and sensors), characterised in terms of their types (for example UAVs and UGVs), locations, readiness status, and so forth. One element of the sensor-mission assignment problem is to match available types of asset to IRs, to give the coalition commanders an at-a-glance view of feasible solutions. This set of feasible solutions is then used to guide the allocation of actual assets to cover the IRs as optimally as possible. Allocated assets will then be configured for deployment in the operating environment. As the sensor network operates, information will be disseminated and delivered to users, and the operational status of assets will be monitored. Both the ongoing monitoring, and the appearance of new tasks and ISR

[1] https://www.usukitacs.com/?q=node/3053
[2] https://www.usukitacs.com/?q=node/3344

[3] Thanks to Paul Smart for this image, taken from the TA4 "humanitarian intervention" scenario.

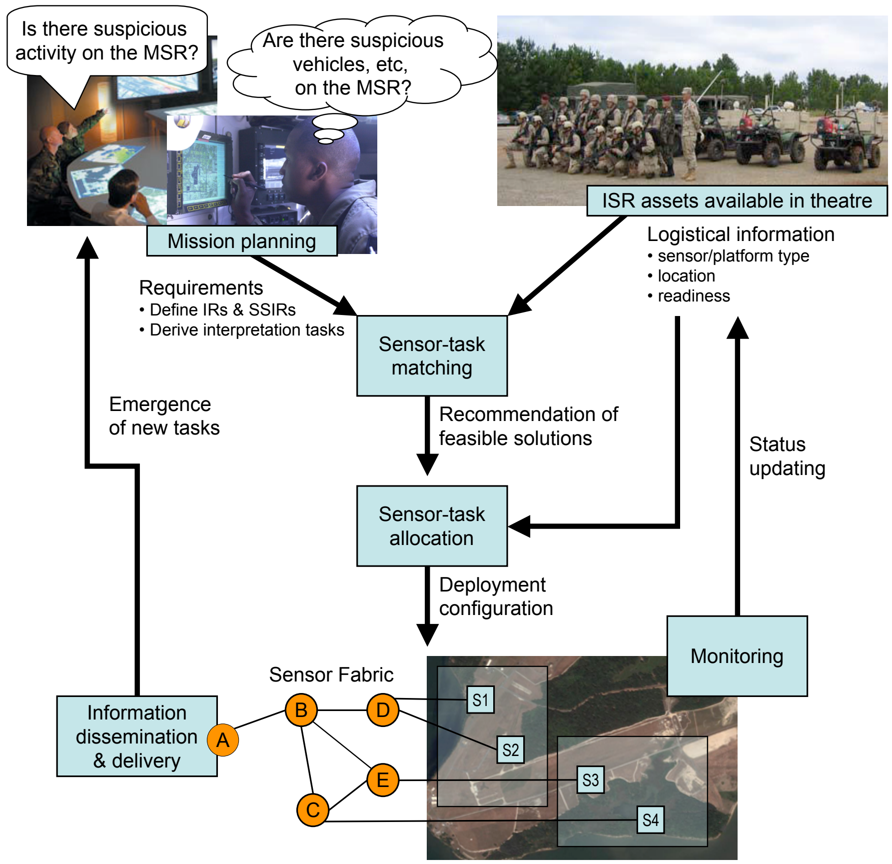

Fig. 2. An approach to sensor-mission assignment (adapted from [1])

requirements, can cause the coalition commanders to reassess the sensor-mission assignment solution. This whole process is illustrated in Figure 2.

Within this overall approach, Project 8 is developing a suite of solution components intended to fit together to solve the larger sensor-mission assignment problem. This paper covers the following (as these are all works in progress, the walkthrough uses "baseline" versions as described in the cited works):

- a knowledge-based reasoner for sensor-task matching, as described in [5];
- a collection of sensor-task allocation algorithms, as described in [6];
- the Sensor Fabric, as described in [7].

In addition, the walkthrough indicates how the acoustic sensor fusion work being undertaken in Project 9, as described in [8], can potentially be incorporated.

Figure 3 provides a layered view of the conceptual architecture, illustrating the various interdependencies. Conceptually, the user is at the "top" while the operating environment (assets and tasks) is at the "bottom". Dissemination of information to users depends both on the allocation of assets (to meet information requirements) and the Fabric (for data transport). Allocation depends on sensor-task matching, which depends on a set of knowledge bases and ontologies [9]. The ontologies describe concepts in the real-world environment (sensors, tasks, etc) which in turn depend on existing representations of these in terms of task thesauri and the Sensor Fabric interfaces.

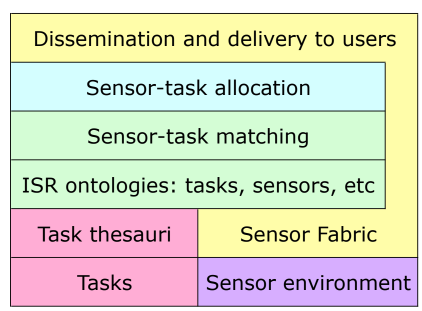

Fig. 3. Layered architecture

III. WALKTHROUGH

For the first time, we consider the complete end-to-end process of sensor-mission assignment, beginning with the definition of information requirements, and ending with delivery of actionable information and intelligence. The walkthrough consists of the following step-by-step activities:

1) Define a set of *information requirements* (IREQs) for the mission(s);

2) Derive a set of *scenario-specific information requirements* (SSIRs) from the set of IREQs;
3) Derive a set of *interpretability tasks* (ITs) from the set of SSIRs;
4) Match each IT to *sensing requirements* (determine the required intelligence (INT) types and NIIRS-style ratings where possible — see below);
5) Apply the knowledge-based reasoner [5] to identify *package configurations* (PCs) which satisfy the sensing requirements
   — factor in availability, weather, type-level policies, etc;
6) Apply the sensor-task allocation algorithms [6] to instantiate the PCs
   — factor-in location, utility, cost, etc;
7) Deploy using the Sensor Fabric [7];
8) Filter, deliver and disseminate actionable information and intelligence (I2);
9) Based on received I2, add, modify or delete IREQs; go to step (2) and repeat.

These steps are considered in more detail below.

Note that the walkthrough isn't meant to imply a centralised approach, with the entire coalition operating in lockstep: one set of IREQs, yielding one set of SSIRs, and so forth all the way down to one Fabric-based deployment. In reality, there will be distribution, with a number of communities of interest within the coalition, each with their own IREQs, SSIRs, etc, leading to distribution and competition at and between multiple levels in the architecture.

Step 1

The coalition commanders will identify many information requirements. We will focus on just one example IREQ and examine in detail how the sensor-mission assignment techniques attempt to meet this requirement:

"Is there suspicious activity on the MSR road?"

Ultimately, the I2 delivered to users is intended to help answer this kind of question. Depending on who the user is, and what their perspective is on the field of operations, they may want to receive different kinds of I2. For example, a headquarters commander may be looking for connections between incidents detected at multiple locations along the MSR. A patrol leader may be primarily interested in incidents near their location but, as events occur, may wish to expand the radius of their area of interest. So we see a need to associate each IREQ with filters for information dissemination. We will return to this point in Step 8.

Step 2

Each IREQ is broken down to a set of scenario-specific information requirements (SSIRs), for example:

- "Are there suspicious vehicles on the road?"
- "Is there suspicious pedestrian activity along the roadside?"
- "Are there suspicious objects located near the road?"
- etc

Note that we don't currently offer any support for this stage; we assume that it is largely a manual process, carried out by a trained and experienced analyst. We could envisage some degree of decision-support here: for example, if the activity is to an extent recognition-primed [10] — people do what's usually done for this kind of IREQ — then we could imagine a tool that uses a technique such as case-based reasoning to recommend and adapt similar previous sets of SSIRs. (Doing this would require some degree of machine-processable representation for the IREQs and SSIRs, however.) Another kind of support is offered by the combination of this and subsequent steps, allowing an analyst to "try out" possible SSIR breakdowns and discover if it's possible to resource them by applying the matching and allocation procedures.

An interesting question here is whether the relation between IREQs and SSIRs is one-to-many or many-to-many. The latter could arise due to overlaps among the SSIRs for different IREQs. For example, if there is another IREQ concerned with tracking the movement of potential insurgents in an area-of-interest that overlaps with the MSR, then detecting suspicious vehicle activity on the MSR could be a SSIR for this other IREQ also. The question is interesting because, we ultimately allocate resources to cover the SSIRs, we may wish to factor-in such IREQ-SSIR relationships. Should, for example, we give more "weight" to resourcing an SSIR that relates to multiple IREQs?

Step 3

The SSIRs need to be broken down further before we can match them to sensing types. We need to identify the *interpretation tasks* within each: what kinds of things do we need to detect, identify, distinguish, construct, etc. In our example, the SSIRs require detection of physical things (vehicles, people, objects) and also some characterisation of intent ("suspicious"). The results of this breakdown will look more like a set of pseudo-database queries:

- "detect vehicles where vehicle type or behaviour is suspicious"
- "detect people where person type or behaviour is suspicious"
- "detect object where object type is suspicious"
- etc

Our aim is to identify all sources relevant to these pseudo-queries. For the first two in our example, we need data from which we can detect vehicles/people and classify them according to type and behaviour. If we can get the raw data (e.g. an aerial photo mosaic of the MSR, at a resolution allowing vehicles/people to be distinguished) then this could be given to a human analyst to interpret. Better still, we should identify information processing assets (e.g. classifiers) that can process the data to highlight more specific features; for example, classify a vehicle as a type of SUV known to be used often by insurgents, or use biometrics to detect that a person is suspicious.

Clearly the nature of the intended recipient is important here (and this step has a complex relationship with information dissemination). Taking our example of the HQ commander and the patrol leader, the former may want interpretability at the level of a complex biometric analysis, face-recognition, etc, while the latter may be satisfied simply with the detection of movement, because the patrol can then investigate and judge if the activity is suspicious (and generate HUMINT).

Step 4

Once we've identified the interpretation tasks within each SSIR, we need to know the kinds of data that are interpretable to answer these: for example, visible imaging, radar, acoustic, etc. An established way way to do this in Intelligence Requirements Management (IRM) is to use the National Imagery Interpretability Rating Scale (NIIRS) for various kinds of imagery intelligence[4]. NIIRS covers Visible, Radar, IR, and Multispectral imaging and, for each, "provides a means to directly relate the quality of an image to the interpretation tasks for which it may be used". For example, identification of vehicles by type is achievable by Visible NIIRS 4 and Radar NIIRS 6.

We have recently built a proof-of-concept knowledge base (KB) for part of NIIRS, allowing a user to select interpretation tasks in terms of three operations (detect, identify, distinguish) and a range of "detectables" (ground, air and maritime vehicles, buildings, etc). The KB infers which imagery types and NIIRS rating levels are appropriate for each interpretation task. For example:

- Identify(Vehicles) $\rightarrow$ { Visible-4, Radar-6 }

Note that in steps 3-4 we are moving from a set of "soft" (human-interpretable) information requirements to a set of "hard" (machine-processable) requirements, to enable use of the subsequent reasoning, allocation, and deployment processes.

Further discussion of the relationship between NIIRS and our Project 8 techniques appears in [11].

Step 5

As detailed in [5], our knowledge-based matching system, SAM (Sensor Assignment to Missions) is able to identify *package configurations* (PCs) of available sensor/platform combinations which collectively provide sets of ISR capabilities. These capabilities include types of sensing (ACINT, IMINT, RADINT, etc) as well as "environmental" capabilities such as fog or foliage penetration, and suitability for various kinds of ISR task (such as constant surveillance, which implies persistent coverage of a potentially-large area of interest). The SAM software application (see [1]) allows a user to indicate their areas of interest (AoIs) on a map, and specify the ISR capabilities required in each AoI. The application then recommends a ranked list of PCs, in which each PC collectively provides the whole set of required ISR capabilities across all the AoIs — see Figure 4. Ranking of the PCs can take account of factors such as their cost and ownership (note the screenshot shows US vs UK-owned assets).

[4]http://www.fas.org/irp/imint/niirs.htm

The goal is for the SAM reasoner to use the NIIRS ratings in identifying suitable package configurations. Currently, SAM uses INT types but not NIIRS values. So, for example, we can currently ask SAM for IMINT or RADINT, but not "IMINT at NIIRS 4" or "RADINT at NIIRS 6". However, adding the NIIRS rating to the sensor types is expected to be straightforward and will be done in the next version of the tool.

We don't have access to NIIRS-style ratings for acoustic intelligence. However, for the vehicle identification task, we are aware of work in P9 that uses ACINT (from acoustic sensor arrays [8]). Adding this knowledge to our KB would allow SAM to suggest (at least) three platform configurations to meet the first SSIR:

- UAV with Camera (rated $\geq$ NIIRS 4)
- UAV with SAR (rated $\geq$ NIIRS 6)
- AcousticArray with ACINTSensors[5]

SAM will take into account other relevant factors. For example, let's say the MSR road is prone to fog at this time of year, so we'll need FogPenetration capability. Moreover, let's assume the Camera type in the first PC above isn't known to have this capability, but the SAR and ACINTSensors do. Note that SAM is taking account of advertised asset availability, using inventory/catalogues for the coalition as a whole. As highlighted in [2], it is conceivable that a coalition member may not want to expose the full capabilities of its sensors. So, for example, a partner could share with the coalition that they have Camera-equipped UAVs, but withhold the information that the Camera does in fact have FogPenetration capability.

Another way in which SAM could take account of policy information at this stage is where there are policies governing the use of particular types of assets. For example, there may be some agreement in force that restricts the use of airspace above the MSR, ruling-out use of any Aerial platforms, including UAVs. But let's assume this is not the case here, and so the UAV-with-SAR remains a viable option for the following stages.

Another important point here is that meeting the SSIRs is likely to involve not only direct sensing (gathering data) but also post-processing and levels of fusion. It's been our intention to identify the need for information processing and fusion assets in package configurations, though our knowledge bases currently don't include them. For example, the acoustic array solution requires analysis of the data, such as provided by the ontologically-mediated classifier being developed in P9 (let's call this information processing asset the "P9 Vehicle Classifier", or P9VC). Performance of the P9VC also depends on the availability of semantic data such as weather, position, threat level which ought also to be factored-into the package (call these assets "P9VC Semantic Data", or P9VCSD). So the full PC description could be something like:

- AcousticArray with {ACINTSensors, P9VC, P9VCSD}

[5]This assumes AcousticArray is the platform, and ACINTSensors the sensor type.

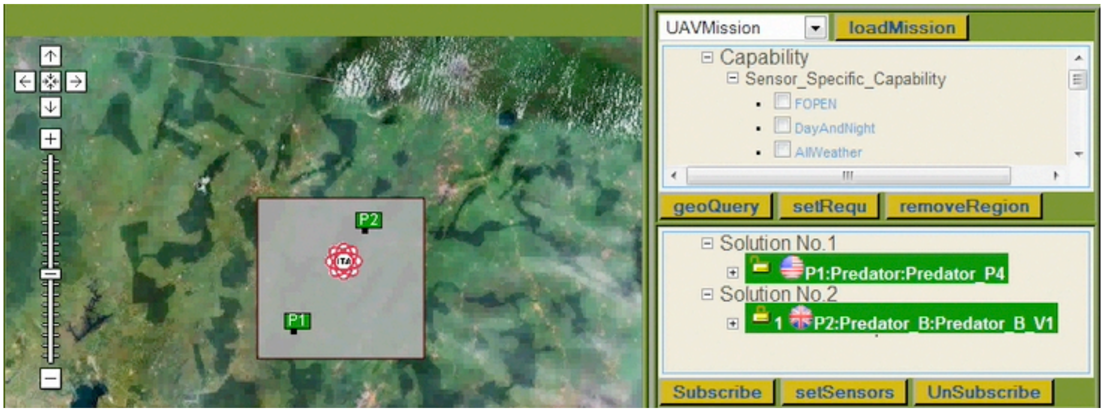

Fig. 4. Screenshot of the Sensor Assignment to Missions (SAM) application

Step 6

The allocation algorithms generate and assign "bundles" of instances, as specified by the PCs. As introduced in [6], the space of possible bundles is significantly reduced by introducing the notion of a *bundle type* (BT). A BT is an intensional definition of a set of bundles of sensors that can satisfy a task, in the form of a set of constraints defining the structure of a bundle, including the types of sensor a bundle should contain, and cardinalities. For example:

- "exactly 2 ACINTSensors"
- "at least 1 RADINTSensor and at least 1 IMINTSensor"

In our current approach, BTs are created by post-processing the PCs produced in Step 5, to add the cardinality constraints, using pre-defined configuration knowledge, for example:

- at least 1 UAV with at least 1 Camera
- at least 1 UAV with at least 1 SAR
- at least 1 AcousticArray with exactly 2 ACINTSensors

As introduced in [6], the sensor-task allocation stage includes a procedure that generates bundles from the available asset instances based on the BTs. Our current thinking here involves identifying particular types of sensing tasks, with a corresponding model for computing the joint utility of bundles. The two example tasks currently are:

- *Constant Surveillance*[6], defined as "requiring any available sensing capabilities in the proximity", which uses a joint utility model based on cumulative detection probability (CDP) inspired by [12];
- *Acoustic Target Detection*, defined as "to be accomplished using only acoustic sensors", which uses a model based on relative positions of two ACINT sensors to the target.

For our two remaining PCs, the UAV solution corresponds to constant surveillance and the AcousticArray solution corresponds to acoustic target detection. When we generate bundles (in this case, consisting of UAVs or pairs of ACINT sensors) we compute joint utility based on the relevant model (CDP or distance, respectively). In the current approach, utilities are comparable only when the same joint utility model is used; so, for example, we can determine the "best" bundle for a constant surveillance/CDP solution, or the "best" for an acoustic/distance solution, but we cannot determine the "best overall" solution because the CDP and distance utilities are not comparable.

Note that it's at this point we factor-in things like the location and operational status of the asset instances. To assign a UAV, it has to be locatable in the MSR area; to assign fixed-location AcousticArrays, they need to be proximate to the MSR. Similarly, the bundle generation procedure and joint utility calculations are intended to take account of things like degraded performance due to battery life, damage, and so on.

In future, we will also need to factor-in access rights to the assets: we can only assign assets to a bundle where the owner of the corresponding task has the right to use that asset in that way [2].

Step 7

Once we've assigned instances we can deploy them by configuring a topology on the Sensor Fabric, etc. For example, in the acoustic solution case, there could be something like the topology shown in Figure 5 where (focussing on the grey nodes): $S1$ and $S2$ are ACINTSensor instances, $S3$ is P9VCSD semantic data, all three of which feed into E which is a P9VC instance, which in turn relays data to B then A both of which are set up to handle dissemination and filtering operations.

The SAM application described in Step 5 provides a basic level of integration with the Fabric, as outlined in [1]. We intend to expand on this functionality in the near future.

Step 8

Users can subscribe to sources on the Fabric to meet their I2 needs. As shown in Figure 5, the user has subscribed to I2 relating to the "Are there suspicious vehicles on the road?" SSIR. Basic subscription functionality using RSS feeds is currently offered by the SAM application.

[6]The term "constant surveillance" is drawn from the CALL thesaurus: http://call.army.mil/thesaurus/toc.asp?id=8394; it has been pointed out that the term "persistent surveillance" might be more appropriate.

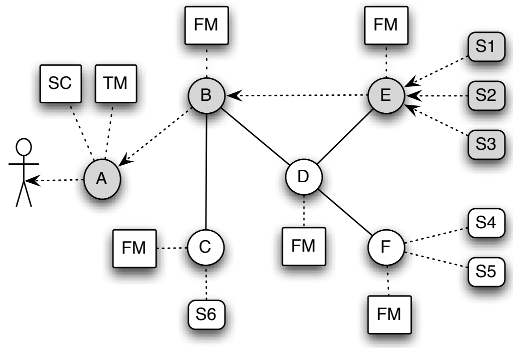

Fig. 5. An example Sensor Fabric configuration, taken from [1]

Depending on who this user is, the data may be delivered, filtered, and/or presented differently. For example, a base commander will probably want an overview of all activity along the MSR, rendered on their laptop screen at HQ, while a patrol leader operating near the middle of the MSR may want only to know of suspicious vehicle detections near their position, delivered as short text messages to their PDA. Initially, Project 8 plans to use rule-based filtering according to task and command level; going further, learning-based filtering using historical data will be investigated [13]. As noted in Step 7, filtering can be accommodated by appropriate configuration of the Fabric.

Step 9

As the situation evolves, new IREQs appear. For example, imagine a patrol leader reports a large herd of migrating wildebeest crossing the MSR road and, as these are a protected species, it becomes necessary establish the extent and cause of the migration, and maybe look for an alternative MSR. Back to step 1!

IV. Discussion and Conclusion

Even though this walkthrough focussed on a single information requirement in a simplified context, it has still revealed a number of gaps where our current suite of techniques do not quite fit together into the overall approach shown in Figure 2.

A. *Supporting Articulation of Requirements*

Currently we offer no support for articulating, analysing, and breaking down IREQs to SSIRs to ITs in Steps 1–3. Should we be aiming to provide any assistance at this stage, or seeking to integrate with other US/UK work in this space? The link from IREQs to SSIRS to ITs is important because ultimately it is the set of IREQs that our whole approach is trying to serve. If the tasks become formalised and machine-processable only at the IT level, then we may miss some opportunities to make maximum use of the available assets in a flexible, dynamic, and agile way — which after all is the main goal of Project 8.

At the asset allocation level, the issue is to maximise utility to the interpretation tasks: that is, give the maximum interpretable data to the SSIRs. We want to be able to share data among SSIRs wherever possible. So, for example, if two (or more) SSIRs need detection of vehicles in the same are of interest, implying Visible NIIRS 4 or Radar NIIRS 6 data, then we can share assets between them (e.g. taking into account sharing policy, command and control, etc).

However, there are many subtleties in going from SSIRs to interpretation tasks. The difference between "detect vehicles" and "detect suspicious vehicles" raises a lot of issues. It's unlikely we'll be able to define a software procedure that can directly answer such an SSIR; instead, we'll be looking for sources of data that, together with post-processing and classification, can give an analyst as much evidence as possible to make a judgement. QoI/VoI will surely be a key issue here, as will the role of HUMINT (which we've been neglecting for now). The key to success would seem to be to create a human-machine cooperative process that helps in separating wheat from chaff, and allows analysts to make the best of whatever information they can get.

Another gap in our current approach is the retrieval and reuse of previously-collected information ("collect once, use often"). We won't always need to generate new data to address a SSIR. There will be "known knowns" — existing pertinent sources we can retrieve. How do we describe, index and access these? We want to avoid "unknown knowns" — things we don't know we already know.

B. *Intelligence Requirements Management*

More work is needed to incorporate information processing and fusion components into the overall approach. The suggestion above of adding items like P9VC and P9VCSD to PCs is a naïve one and needs further development. In our recent work on bundle types (Step 6) we acknowledged the need for additional configuration constraints, such as cardinality (e.g 2 AcousticArrays with ACINTSensors, 1 P9VC, etc) and location (e.g. 1 UAV covering the northern MSR, 1 UAV covering southern). More kinds of constraints are surely going to be needed here.

There is also the open question of resource scheduling, which we've been neglecting thus far. For example, we may ideally need a collection of sensing types to provide a complete set of interpretable data for some SSIR, but they may not all be needed at the same time. For example, it may be enough to gather the ACINT data (needing the AcousticArray assets) now, and do the classification (needing P9VC and P9VCSD assets) later. This is related to the important issue of *sensor cueing*, where one sensor may produce data that cues the use of another sensor to gather further data. In our motivating example, the ACINT/UAV options are not necessarily an either/or choice — in reality, the acoustic array may cue a UAV to check out a suspicious SUV.

If we accept that SSIRs are the essential "tasks" for which we need to collect data, then we want to be sure our allocation/bundle algorithms fit these in the best way. Note the case above where an SSIR can be addressed with more than one approach, leading to a choice of joint utility model. How to we handle this so we maximise the potential utility of the whole ISR network, while bearing in mind that sensor information can be complimentary.

In general, the whole approach needs to be better integrated with IRM practice; in particular, we need to look at incorporating ISR/ISTAR matrices into our work.

Finally, we have only begun exploring the integration of matching and allocation with dissemination and the Fabric, in the context of policies on access to resources. While we have done some initial work on incorporating policies governing access rights to sensing assets, we need to extend this to access rights to information and intelligence products. Also, while we have considered policies for "sanitizing" the capabilities of assets (see Step 5) we have not yet considered sanitizing of I2. As ever, the goal is to maximise the utility of all ISR assets (sensor, platform, processing, and intelligence products): give all stakeholders as much as is possible; deny as little as possible.

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Appendix - Glossary of acronyms

ACINT	Acoustic Intelligence
AoI	Area of Interest
CPD	Cumulated Probability of Detection
I2	Information and Intelligence
IR	Infrared
IREQ	Information Requirement
ISR	Intelligence, Surveillance and Reconnaissance
IT	Interpretability Task (as in NIIRS context)
IMINT	Imagery Intelligence
IRM	Intelligence Requirements Management
MSR	Main Supply Route
NIIRS	National Imagery Interpretability Rating Scale
PC	Package Configuration (of sensors and platforms)
RADINT	Radar Intelligence
SAR	Synthetic Aperture Radar
SSIR	Scenario-Specific Information Requirement
SAM	Sensor Assignment to Missions
SUV	Sports Utility Vehicle
UAV	Unmanned Aerial Vehicle