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Sensor Management Issues for SAR Target Tracking and Identification

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Abstract: Sensor-management in tracking consists of sensor mode control and scheduling, target selection, and situation assessment. In a dynamic environment, airborne radar necessitates active mode control for the acquisition of a synthetic aperture radar (SAR) image of stationary targets. This paper discusses the control, fusion, and management of SAR sensors for target tracking and identification.

1.0 Introduction

An airborne or spaceborne platform, that includes radar, requires active control for determining when to collect and integrate radar scans to form a SAR image as shown in Figure 1 and Figure 2.

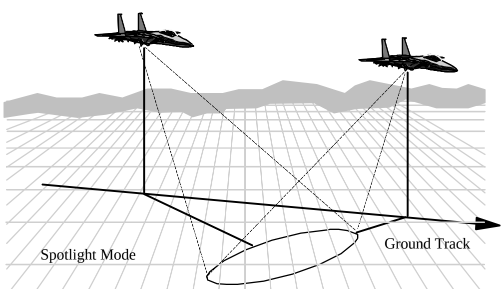

Figure 1. Spotlight Mode Radar.

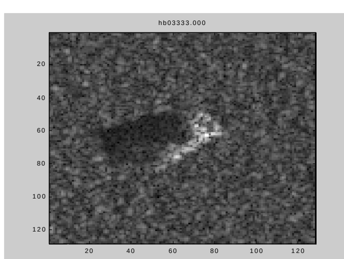

Figure 2. Synthetic Aperture Radar.

Target tracking is the maintenance of a target's kinematic information of position, velocity, and acceleration in time and space. In the case of multiple targets, the tracker could use identity (ID) information to determine targets from cluttered measurements. While many sensors may be used to collect the kinematic measurements such as cameras and infrared sensors, synthetic aperture radar (SAR) will be discussed since SAR is distance and weather invariant [4]. Some of the complications of using SAR for target tracking include when to activate the radar mode, resolution selection, and slewing position for the radar to maintain an image center. Limitations of SAR for tracking include fixed collection time, inherent stationary assumptions, and partial observations. Benefits of SAR for tracking include rich spatial information, all-weather capability, and ability to discern target types. Assumptions required for using SAR for tracking include non-overlapping solid targets, detected target stationarity for SAR collection initiation, and complete collection of an image. When tracking information is included with SAR imaging, a sensor fusion system can perform situation assessment. The key to the information integration is the sensor manager which determines when to activate the SAR.

2.0 Background

Radar has been around for over 50 years and researchers have been working with radar for automatic target recognition (ATR) [3,4] and single-target tracking [2,11,16]. One problem that arises in tracking multiple targets from SAR images is that the radar mode has to be determined *a priori* to the scan. Sensor management (SMgt) can assist in determining when to activate the SAR radar[8]. Using multiple radars displaced in time or space can assess a target's motion [2,7,11]. For example, high-range resolution radar (HRR) is a mode for moving targets and SAR is the mode for stationary targets. HRR can be used for target ID, but at a lower ATR confidence value than SAR [4,16]. Thus, as a target stops and moves, a tradeoff exists for the radar mode of selection.

While many issues arise from the mathematical formulation and clutter mitigation using SAR, [7], the fusion research community [1,6,15] has not addressed how to use SAR in a sensor fusion model to assist in target tracking and ID. Specifically, we wish to address the scheduling of SAR collections for improved target tracking. Popoli [13] describes the sensor scheduling problem as "given the ability to decide which tasks are important .., how do we set up a time line of tasks for the sensor to perform." Popoli's suggestions of *best first*, a myopic method, and *brick packing* do not apply for SAR, since sensor-target matching is uncertain. We seek to address SMgt for SAR to address the sensor-target uncertainty. The United States Air Force Research laboratories has pioneered some concepts for SMgt [12]. This paper highlights SMgt concepts using for SAR target tracking.

Section 2 discusses sensor fusion with reference to the JDL fusion model. Section 3 addresses SAR ATR for ID with Section 4 introducing tracking issues. Section 5 lists sensor management issues for using SAR in target tracking and Section 6.0 draws conclusions.

2.0 Problem Formulation

In order to use SMgt for SAR target tracking and ID, we discuss the JDL sensor fusion model, multilevel fusion, and SAR mode control. Figure 3 presents our additions to Steinberg's [14] confusion of terminology to highlight SMgt.

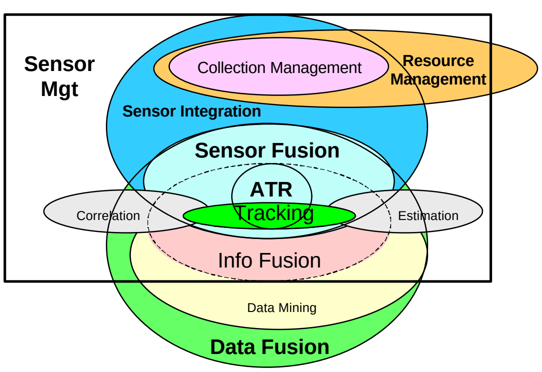

Figure 3. Confusion of Terminology[14]

From Figure 3, we see that SMgt includes tasks of information fusion, but does not completely perform off-line data mining and resource management. This implies that SMgt participates in data fusion but is essential to information fusion. To further understand the role of SMgt we address the definitions of the JDL sensor fusion model.

2.1 Sensor Fusion – JDL Model

One of the prominent information fusion diagrams is that of the Joint Director's of Labs (JDL) fusion model of Steinberg, Bowman, and White [14]. The JDL model consists of five modules, and is shown in Figure 4.

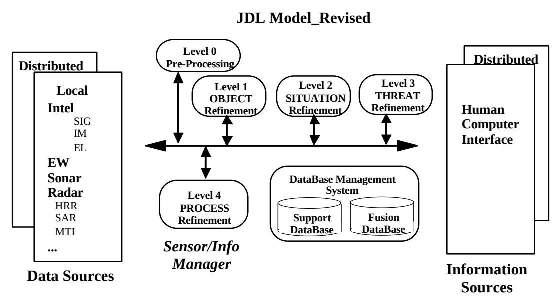

Figure 4. JDL Revised Model [14]

Level 0 – Sub-Object Data Assessment: estimation and prediction of signal/object observable states on the basis of pixel/signal level data association (e.g. SAR imaging);

Level 1 – Object Assessment: estimation and prediction of entity states on the basis of observation-to-track association, continuous state estimation (e.g. kinematics) and discrete state estimation (e.g. target type and ID);

Level 2 – Situation Assessment: estimation and prediction of relations among entities, to include force structure and force relations, communications, etc. (e.g. multiple targets);

Level 3 – Impact Assessment: estimation and prediction of effects on situations of planned or estimated actions by the participants; to include interactions between action plans of multiple players (e.g. assessing threat actions to planned actions and mission requirements);

Level 4 – Process Refinement (an element of Resource Management): adaptive data acquisition and processing to support mission objectives (e.g. sensor management).

The fourth module is that of *sensor management*, or the control of sensors. In this case, SAR SMgt is a function of the time to collect an image from radar scans, where to point the sensor for target estimation, and ATR correlation to a database. The sensor manager must utilize information from the other JDL levels to predict the next state position of the target and can help overcome SAR tracking issues.

2.2 SAR Target Tracking Issues

From Figure 1, we can use spotlight mode radar to capture an image of a target as shown in Figure 2. However, with uncertainty from measurement clutter, one needs to know where to point the radar, which is a *slewing problem*. In order to enhance track quality, the fusion of tracking and ATR information can aid in determining the number, type, and orientation of targets to effectively point the radar.

Measurement uncertainty might result from sensor errors, partial scans, and incorrect pointing of the radar. Target uncertainty results from *incomplete knowledge* and affects the prediction of the number of targets. Incomplete knowledge can be represented as a set of information for what is known, appended with a component that captures the unknown information. Sometimes the known information is improperly assessed and the most likely probability is assigned to the target, as in the case of misclassification of targets. By capturing unknown information from other sensors we can capture incomplete knowledge.

We use SMgt to control the SAR sensors assigned to a set of targets being tracked through accumulated fused evidence. Evidence accumulated can be accomplished from a set of sensors; however there is a *complexity problem* when one tries to obtain all the information about a target for classification and ID at each time update. By assessing the set information, a belief measure can help weigh the evidence update in time, reflect conflicting target measurement, and compare the different resolutions of the sensors. The resolution level affects a target's ID, such that the confidence level from a belief increases for correct classification.

The most important SAR tracking issue is that of detecting the *transitory nature of the target*. We explore the use of SMgt to control the expansion of unknown targets to determine whether a detected target is in a *transitory* moving-to-stationary or stationary-to-moving mode. The next section will explore data, information, and SMgt in fusion to determine if a target is in a stationary or moving mode to assess the ATR problem of the target kinematic transitions.

3.0 SAR Target Identification

Synthetic Aperture Radar is distance and weather invariant which makes it a robust sensor for monitoring a set of targets. Typically, the radar operates in a spotlight mode, where the radar beam is slewed [11], or continually steered to constantly illuminate the same target from all positions of the flight path, as shown in Figure 1. Spotlight mode SAR needs to detect a stationary target from which to start the slewing of the radar to lock onto the target from the moving platform.

SAR target ID is similar to image processing techniques [4]. The difficulty with using getting a SAR image is that targets need to be moving at a slow speed, or one in which the sampling time can collect the target within the time allocated. Typically, a SAR image takes up to 10 seconds to construct. For sampling purposes, the target should be moving at a speed such the movement is not greater than 5 km per hour [7]. If the target is moving faster than this rate, a portion of target can be assessed from the Doppler shift and is usually considered as HRR. Obtaining a SAR image is much like a camera; however, the quality of returned image is not as sharp as a camera and is usually blurred from inherent Doppler processing of the image.

3.1 SAR ATR

Consider Figure 2 as an acquired target image. By assumption, the aircraft has a single SAR sensor able to detect targets like ground stationary tanks. Any pixel in the SAR image can be measured independently of the others, and the outcome of each pixel is a random variable indicating the magnitude of the energy return from the radar. Clustering these pixel measurements allows for a decision to be rendered as to which orientation and what target type is observed. The assumption is that the target type, e.g. tank, is known *a priori* and the orientation information will further help reference target features for classification. Learned-observation information metrics are considered stored in memory and the ATR algorithm is to compare the SAR image measurements to a known database. From a track history, the target ID is an assessment of the target classification information.

The static-target detection and ATR problem is to determine what sequence, the minimum pixels to cluster, and what ATR method to use for matching the observation to the database. These actions should provide the highest probability that the target orientation and type will be isolated. After *M* measurements and comparisons to *O* observations, a "*value of information*" will determine the information-theoretic ATR match. If a threshold is achieved, a preliminary orientation and target-type is determined which allows the classification routine to update the tracking algorithm.

3.2 SAR Sensor Fusion

Since the radar information takes time to process, other sensors can aid in obtaining a track history, or at least maintaining the general location of the target. Such additional sensors could include intelligence (INT) sensors [15] of imagery (IMINT), signature (SIGINT), and human (HUMINT). IMINT includes 2-dimensional data such as SAR, ISAR, line-of sight surveillance cameras, FLIR systems, and moving target indicators (MTI). SIGINT includes 1-dimensional sensors such as HRR, electronics (ELINT), and communications (COMINT). N-dimensional sensors are those that give a rich amount of information such as HUMINT and techniques for processing group and force structures. Each of these radar and non-radar sensors can assist in target tracking and ID.

4.0 Target Tracking

Tracking multiple targets requires kinematic maintenance. In the case of multiple moving targets, the sensor manager must estimate the targets' position and predict where the target will be at a future time so as to point the SAR sensor in the direction of the expected target position. As shown in Figure 5, target tracking begins with the detection of a target from an MTI sensor. Using other radar modes, the ATR system could ID a target; however, additional INT data is needed to ascertain the allegiance, intent, and behavior of a moving target. We could employ a hierarchical schedule and prioritization of the INT data collection.

The hierarchical use of the information could be to process low-level features in the radar returns, and high-level information from the INT sensors. Feature extraction can be used for object detection, recognition, classification, and ID. For tracking, image content and registration are important for time and location referencing. Additionally, ATR algorithms are subject to capacity constraints. Since the ultimate goal is to render a decision, we will examine a decision-theoretic approach to capture the high-level INT information. The control of this information is from the sensor manager.

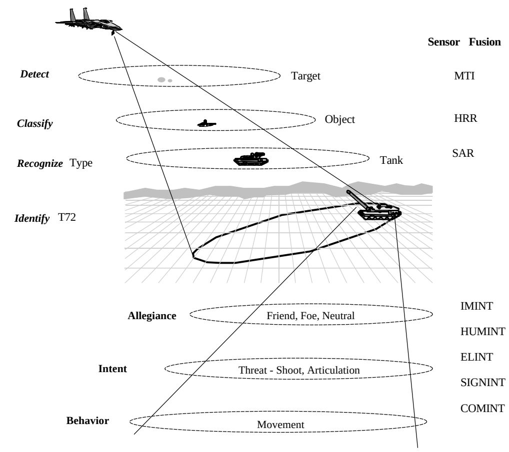

Figure 5. Fusion Management.

5.0 Sensor Management

Tracking multiple targets from a SAR sensor can not be accomplished since SAR is used for stationary targets. While the collection of part of a SAR image is similar to HRR, a degraded SAR image can be used to capture a target's movement, the critical issue to using SAR for target tracking is SMgt or namely, the efficient and effective use of SAR with a set of other sensors.

The other sensors include the INT sensors in 1D, 2D, and nD information. The sensor manager must capture the spatial and temporal aspects of the target. Spatially, resolution is a tradeoff for ID. Temporally, the sensor manager must be able to process targets in an efficient manner. Since the radar antenna is moving to capture the target, the sensor manager must schedule the appropriate time to invoke the SAR sensor. Other sensors can cue the SAR radar for identifying a target and a degraded SAR image can capture moving targets.

5.1 SAR Sensor Scheduling

To use SAR from a collection of sensors, a sensor manager schedule [10] is needed to initiate the activation of the SAR radar mode. The scheduler can

1. Reduce the workload for the operator by automating sensor allocation, moding, and pointing;
2. Prioritize and schedule service requests to meet both integrated flight management, mission completion, and sensor control;

3. Aid in sensor data fusion by coordinating fusion requests with the data collected from different radars in different modes;
4. Support reconfiguration and SAR degradation due to partial completion of an image or loss of image collection;
5. Develop a sensor schedule that optimizes (or at least sub-optimizes) the use of available SAR sensors, and
6. Communicate desired actions to the individual SAR sensors.

We can view scheduling as a function of two tasks: 1) an *information manager* that determines what measurement tasks are required to maintain a level of target ID and track history, and 2) a *SAR scheduler* that allocates time to capturing a SAR image. The tasks are resource, time, and resolution constrained and need to be optimized through a cost function. Since SAR requires that a target be detected as stationary, a situation assessment of multiple targets needs to be determined to detect a moving-to-stationary event transition to turn the SAR mode on and a stationary-to-moving event to turn the SAR radar off. One way to detect the changes in the target movement is through a velocity assessment of the target. In Figure 6, we show one way to control the SAR mode. For this case, we need to use the other sensors such as a tracker to help assess

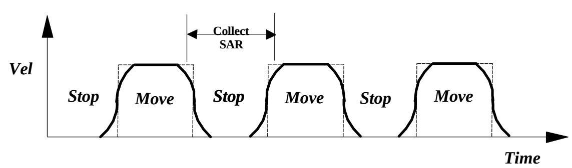

Figure 6. Active Control of SAR radar.

when a target is moving. Thus, the scheduler can determine when to activate the SAR mode.

In the SMgt system, a control of the flow of information is needed. Figure 7 shows that by using external INT information, the sensor manager can prioritize the use of the SAR to capture and update target ID. Getting the eternal tasks, we can use a decision-theoretic approach.

5.2 Decision Theoretic SAR Management

A graphical way to represent a decision analysis is an influence diagram. An influence diagram, based on conditional independence, scales and facilitates reasoning. An influence diagram is a directed acyclic graph. Nodes represent *propositions* such as a decision point (i.e., a world state controlled by the user), an uncertain state of the world (i.e., one not controlled by the user) or user *preferences* (e.g., mission objectives). The notation of influence diagrams shows decision points as square nodes, uncertainties as ellipses, and preferences as diamonds.

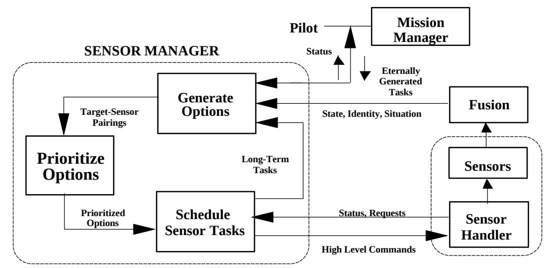

Figure 7. Sensor manager task flow.

A tracker reports a multitarget tracks to the sensor manager. The relevant world states (WS) are friendly, foe, or neutral vehicles, target types, and target articulations. Associated with the world state is a probability distribution of the different states (e.g., the probability that the unknown target is friendly). The sensor manager can either update the track's kinematic state or ID it. If the update sensor action is chosen, the *evidence* will be able to distinguish the direction of the unknown target. If the ID sensor action is chosen the resulting evidence would be one of friend, foe, or neutral or target type. There are conditional probabilities associated with the evidence node. The probabilities are conditioned on the sensor action and the world state. These conditional probabilities represent a high-level probabilistic model of the accuracy of the planned sensor action. Nodes with arcs pointing to a decision nodes are assumed to be resolved before the decision is made. Thus, the pilot is assumed to see the *value of information* gathered from the sensor action before he takes his action. The decisions are assumed to be made with respect to some objectives/preferences. The quantification of these preferences are stored in the utility node as a function. The *utility function* has as arguments the nodes that immediately precede it (e.g., world state, and sensor action). For each combination of these nodes the utility function returns a value that measures the desirability of the situation. In SMgt situations, the overriding objectives are the safety and the successful completion of the specific mission objectives.

Given an influence diagram with the associated probability distributions and utility functions, the reasoning task is to solve for the optimal decision strategy. By optimal we mean the strategy that maximizes the expected utility. Any particular strategy can result in variety of outcomes each with its own utility value. The likelihood of each outcome depends on the outcomes of the uncertainties in the situation. Given a decision strategy, the probabilities of the uncertainties determine the probabilities of each of the utility values. The expected utility of a strategy is the weighted average of the probability of each utility value and the value itself

Inference algorithms are available to carry out the *reasoning task*. The inference algorithms manipulate the probabilities in the diagram to infer the expected utility of each strategy. For example, running an inference algorithm on the SMgt diagram (shown in Figure 8) would compute for each sensor action (e.g., update track and ID) an expected utility. The optimal sensor action would be the one with the largest utility.

To summarize, an influence diagram provides for the representation of uncertainties, decisions, and preferences. Probability distributions are used to quantify uncertainties and utility functions are used to quantify preferences. The reasoning task is to generate how the decisions should be made as a function of the information known at the time of the decision.

5.3 Modeling SMgt Using Influence Diagrams

SMgt is a decision making process under uncertainty directed at information gathering. Several formal mathematical models have been developed for information gathering situations. A general approach developed in the decision sciences is referred to as "value of information". This approach uses probability calculations and expected utility calculations to determine which of many possible information gathering strategies (e.g., what sensor actions to choose) is most effective in understanding a decision.

Figure 8 shows a decision maker (e.g., pilot) whose situation the diagram represents. There is an uncertain *world state* (ws) that interacts with the decision makers decisions to determine his utility. The decision maker has at his disposal sensor actions to get information to reduce his current uncertainty about the world state. At the time of his decision about what information to gather, he already has accumulated some evidence about the world. The new evidence (e) that is gathered is a function of his sensor action (s) decision and the true world state. Evidence informs the decision maker in his second decision of how he should act in the world.

The solution of this problem can be described as follows:

1. The <u>updated probability distribution</u> in the world state as a function of the reported new evidence is found as well as the probability of the new evidence conditioned just upon the sensor action through Bayes Rule:

$$p(ws|e,s) = k\,[\,p(e|w,s)] \bullet p(ws|e,s)$$

$$p(e|s) = \sum_{ws} [\,p(e|ws,s)] \bullet p(ws|e,s)$$

2. An optimal strategy for world actions is determined with the updated probability estimates on world state. An expected utility is computed for each combination of sensor action and new evidence.

$$U(s,e) = \max_{ws} \sum_{ws} [\,p(ws|s,e)] \bullet U(ws \mid wa)$$

3. The optimal sensor action results from maximization of utility over this intermediate utility function.

$$s_{opt} = \arg\max_{e} \sum_{e} [\,p(e|s)] \bullet U(s,e)$$

Time is often an important consideration in sensor situations. In a time-pressured situation, the cost is usually dominated by the loss of opportunity and risk that a decision maker incurs during that delay associated with obtaining the answer. Additional observations can be made if the value of information exceeds the cost. If there is no set of sensor actions for which this criterion holds, we should halt reasoning and take the world action with the highest expected value.

There are several unique characteristics of the SMgt problem as it relates to the classical formulation of decision-analytic management of information gathering:

- Temporal evolution of the system:
- Real-time
- Dependence of the world on sensor actions
- Little visibility of "world" action

For a SAR SMgt problem, we include these characteristics to the influence diagram:

- The division of the world state into <u>two</u> temporally distinct time periods: This separation provides for the *temporal evolution* of the world state as well as for the dependence of the world state on sensor actions

- The impact of sensor actions on the world state results after the sensor actions have been performed.
- The pilot action node from a decision to a chance node. This represents the fact that the sensor manager *cannot control* the pilot actions. The chance node representation will act as a simple model of the pilot that can be used to coordinate sensor actions with anticipated pilot actions.
- Temporal evolution of the belief in pilot actions and mission objectives with mission progress.

Figure 8 shows the SAR SMgt influence diagram. Mission progress would dictate the current tradeoff between being detected and acquiring new targets. Different schedules would be evaluated with respect to both of these objectives and the one that best balances the two objectives would be executed. Another example is that the influence diagram can take uncertainty of target ID in sensor actions. ID sensor actions will be extrapolated to reduce uncertainty in ID, this will lead to higher utilities for pilot actions which are consistent with the ID and INT information. This will lead to an overall expected utility for the action. This utility can be compared with the utilities of other actions (e.g., track update, search). Once the appropriate detections of the target movements have been made, the decision making process has to be able to process uncertain data such as whether the target is actually moving or not to activate the SAR system. In order to accomplish such a task, an influence diagram is proposed to assess the accumulation of evidence in support of the system to determine the correct actions to undertake.

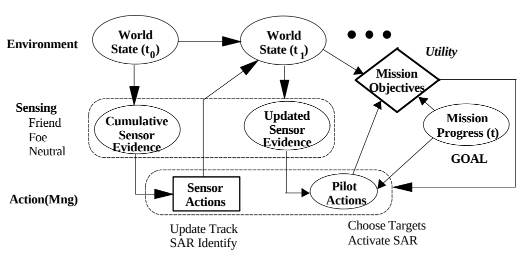

Figure 8. SMgt influence diagram

In the diagram of Figure 8, we are proposing that a "value of information" be assessed to determine whether to activate the SAR system, since the premature activation of the sensor, would invalidate the scan and hence the ATR system.

5.3.1 Updated Sensor Evidence

The updated sensor evidence of ID can augment tracking information with track quality confidence updates. The set-theoretic belief update is an accumulation of fused evidence. The belief update from evidence captures unknown target dynamics to determine whether a detected target is in a *transitory* moving-to-stationary or stationary-to-moving mode. In the case that a target is moving, a 1D HRR profile can be used to classify the target, whereas in the case of a stationary target, a 2D SAR image can be used to determine the target type.

5.3.2 Mission Feedback

We see that mission feedback includes the pilot actions and the sensor state information. We note that the view of the world is a perceptual event [4] in which the human brings together SIGNINT, HUMINT, and IMINT information. Thus, the mission information is useful before the sensor manager can determine when to schedule the next SAR collection.

We note that the information from the feedback helps improve responses or actions to the situation. In the case of multiple targets, we need to know which targets are moving, have had the most recent update, and those that are stationary and are in need of identity update. Using the formulation of set-based belief updates, we can use estimation updates without an explicit report-to-target associations. Thus, while many tracking algorithms use an association update, we would have to only determine from the set of information, what would be needed to ensure that the set of information had an update for the mission at hand.

Using the refined data fusion definition [14]: *Data Fusion is the process of combining data to refine state estimates and predictions,* we see that we ensure that state updates from the sensor manager assist in the data fusion process. It is important to realize that the sensor manager can perform the actions of process refinement:

1. Association – *Planning*;
   When to get a SAR image
2. Estimation – *Control;*
   Which SARs to activate
3. Entity - *Estimation*
   Action for determining the set of targets

Thus, while process refinement captures the many actions of sensor fusion, it is the job of the sensor manager to perform the planning, action, and estimation of the situation and the appropriate use of the sensors. There is a duality between estimation and control as well as association and planning; where *estimation and association* are determining what is happening and *control and planning* determine what to do. Thus, the sensor manager needs the "What and Where" information to determine the "How" information. What is also needed is the "When" and that is the central role of the sensor manager. We propose these other actions for the sensor manager to assist in process refinement:

1. Control – *Scheduling*;
   When to get SAR image
2. Plan – *Prioritizing;*
   Which order to activate SARs
3. Association – *Communicate;*
   Determine the related decision
4. Estimation – *Support*
   Determine reconfiguration of sensors

We feel that these tasks for the sensor manager apply not only to SAR target tracking, but to the JDL model as well. Since prioritizing, scheduling, communication, and support are critical for sensor, data, and information fusion, they provide a basis and necessary actions, that can update the JDL model. Action for determining the set of targets and when to use the SAR information can be surmised from the influence diagram.

5.4 INT Updates

Informational and perceptual updates can aid in the fusion of information. In the case that HUMINT, ELINT, and IMINT data are available, we can determine that it is the sensor manager's job to use the integrated information to assist in the next state actions. Why do we propose this for the sensor manager? Because it is the location where a human would normally be determining which radar modes to activate. Thus, the natural selection for the information fusion and action is that of the sensor manager where the human typically performs this function. By using automated information, it can augment the person's perceptual capability from additional sensory information.

6.0 Conclusions

The paper has overviewed some of the issues associated with using a SAR target tracking, sensor management fusion, and simultaneous target tracking and ID. We have proposed additions to the JDL model that necessitate the inclusion of a sensor manager to perform actions of scheduling, prioritizing, communicating results, and support sensor degradations.

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