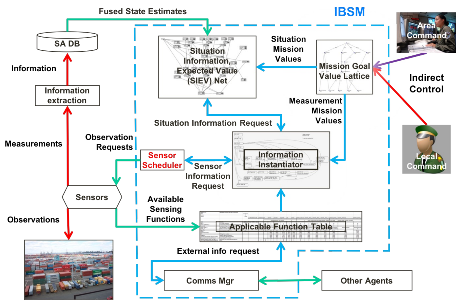
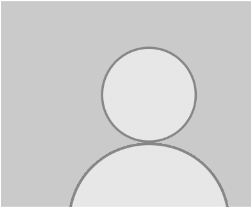




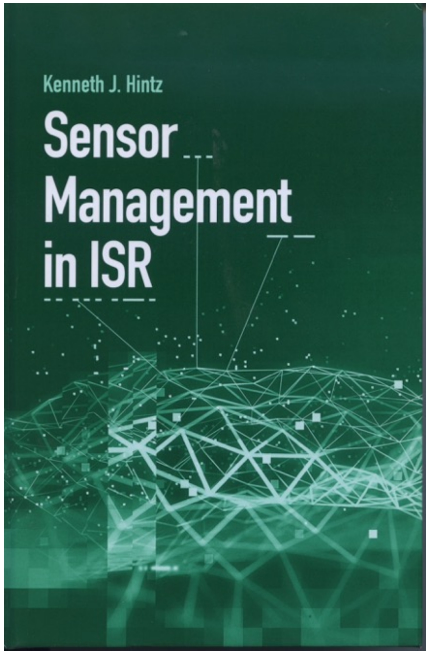
Introduction to Sensor Management

August 2022

Ken Hintz
ken.hintz@perquire.com

TOC *Sensor Management in ISR**

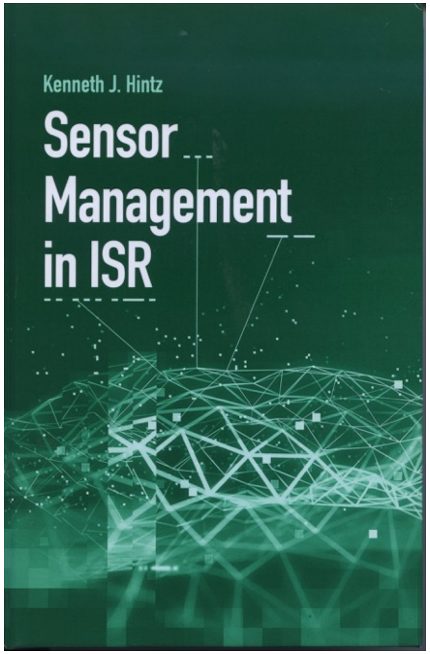
- Introduction To Sensor Management
- Historical Basis For Sensor Management
- Sensor Management Macro Problems
- Sensor Management Micro Problems
- Theoretical Approaches To Sensor Management
- AI For Sensor Management



* *Sensor Management in ISR* (Intelligence, Surveillance, and Reconnaissance), 250 pages, Boston:Artech House, February, 2020, ISBN: 9781630816858

TOC *Sensor Management in ISR**

- MQ-4C Triton: Case Study
- Information Theoretic Approach To Sensor Management
- IBSM Optimization Criterion
- IBSM Implementation Approaches
- Human-machine Teaming For SM
- SM Performance Monitoring
- Future Technologies And Implications



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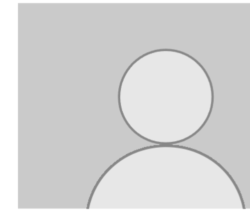
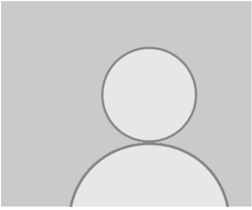
Tutorial Outline

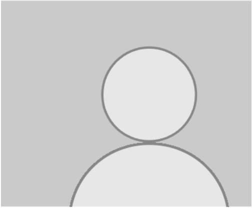


- Basis and need for sensor management (~30 min)
  - JDL Model
  - Definitions
  - Distinction between scheduling & management
  - Motivation for sensor management
  - Types of SM systems
- Historical basis for SM (~15)
  - Pre WW-II
  - Cold war era
  - Vietnam era
  - Current asymmetric warfare & 911
  - Network Centric Warfare

Tutorial Outline



- Macro issues in SM (~30)
  - Political issues
  - Resource constrained
  - Multidisciplinary
  - Competing users
  - World models
- Micro issues in SM (~15 min)
  - Route planning
  - Redundant coverage
  - Data fusion or decision fusion
  - Centralized, distributed, or hybrid management
  - Design considerations



Tutorial Outline

- Theoretical approaches to SM (~30 min)
  - Global, myopic
  - Real-time
  - Naïve & point solutions
  - Normative or descriptive
  - Architectures
  - Networked IOT
  - Game theory
  - Market theory

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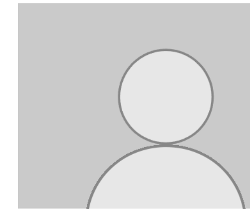
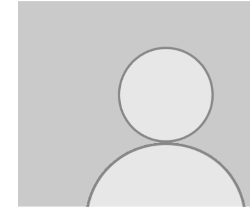
Tutorial Outline



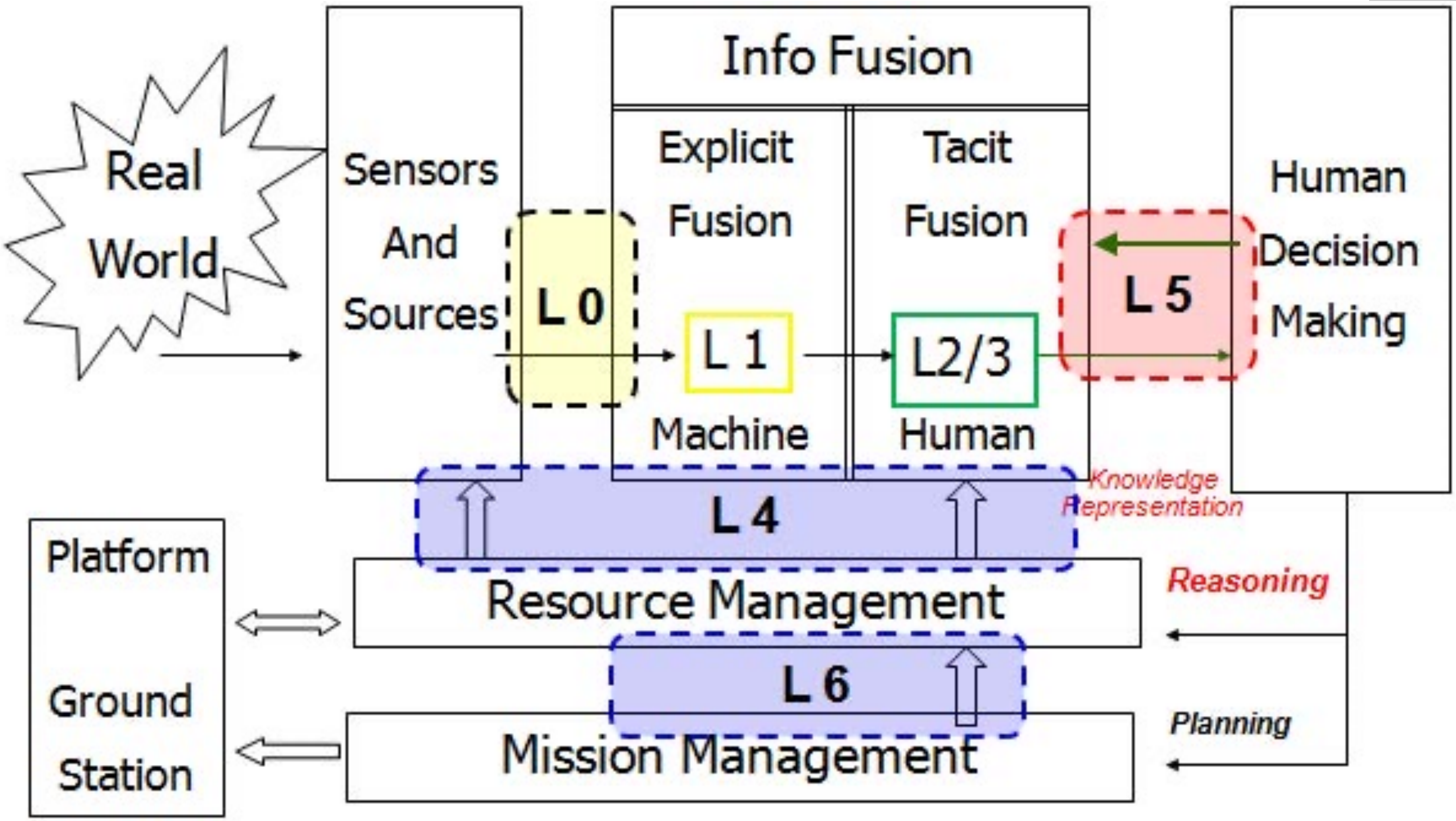
- Information Based Sensor Management (~60 minutes)
  - Motivation for information based sensor management (IBSM)
  - Underlying principle is maximizing expected information value rate, EIVR, from the real world to the mathematical model of the world
  - Situation information vs sensor information
  - Functional decomposition of sensor manager into six orthogonal, realizable components
  - Network of IBSM managed platforms
  - Benefits of IBSM



Basis and need for sensor management

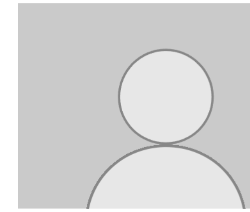
- Context of sensor management in the JDL Data Fusion Model
- Elements of SM
- Basic fusion related definitions
- Distinction between scheduling & management
- Need for sensor management

Relationship of SM to JDL Data Fusion Model *



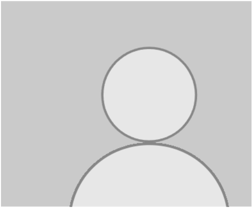
* [Blasch 1]

JDL Data Fusion Model,* Levels 0-3



- Level 0: **Data Assessment**: estimation and prediction of signal/object observable states on the basis of pixel/signal level data association
- Level 1: **Object Assessment:** estimation and prediction of entity states on the basis of data association, continuous state estimation and discrete state estimation
- Level 2: **Situation Assessment:** estimation and prediction of relations among entities, to include force structure and force relations, communications, etc.
- 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

* [Blasch 1]

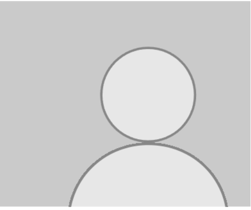


JDL Data Fusion Model* Levels 4-6

- **Level 4: Process Refinement: adaptive data acquisition and processing to support sensing objectives**
  - ***sensor management***
  - **information systems dissemination**
  - **command/control**
- Level 5: **User Refinement**: adaptive determination of who queries information and who has access to information and adaptive data retrieved and displayed to support cognitive decision making and actions
- Level 6: **Mission Management**: adaptive determination of spatial-temporal control of assets and route planning and goal determination to support team decision making and actions over social, economic, and political constraints.

* [Blasch 1]

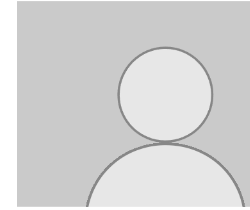
Elements of Sensor Management



- Sensor Management entrails the ***control*** of the information gathering activities which drive the sensor fusion process [Malhotra, 2]
- The ***goal*** of sensor management is to integrate sensor usage to accomplish ***specific mission objectives*** at high performance levels [Musick & Malhotra, 3]
- This functionality requires the ***automatic generation of appropriate tasks***, the mapping of these tasks to a set of feasible sensors, the calculation of the benefit achieved for executing the task, and the eventual optimal scheduling of these tasks. [Shea *et al*., 4]

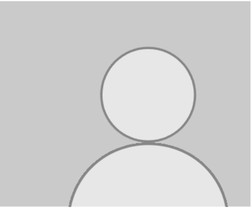
Introduction to Sensor Management, © K. Hintz

Descriptive Definitions of Sensor Management



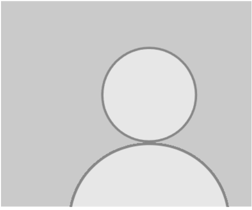
- Sensor management can be described as a system or process that provides ***automatic or semiautomatic control*** of a suite of sensors or measurement devices in a ***dynamic and uncertain environment*** [McIntyre, 5]
- The goal of SMS can be defined as to manage, coordinate and integrate the sensor usage to accomplish specific and often ***dynamic mission objectives*** [Ng & Ng, 6]

Control Definitions of Sensor Management

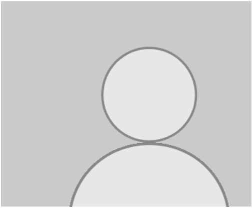


- Sensor management involves the ***control of one or more sensors*** on one or more platforms in an intelligent manner over time to achieve the ***needs of the mission*** being performed by the platform or platforms in question [Buede & Waltz, 7]
- Multi-sensor management is formally described as a system or process that seeks to ***manage or coordinate*** the usage of a suite of sensors or measurement devices in a dynamic, uncertain environment, to improve the performance of data fusion and ultimately that of perception. [Xiong & Svensson, 8]

Prescriptive View of Sensor Management



- View sensors as a ***communications channel*** which transfers ***mission-valued information*** from the real world into a mathematical model of that world for ***use by decision makers***
- The goal of sensor management is to ***maximize the expected information value rate*** (EIVR) of data through the sensors and information extraction processes to produce the minimum uncertainty estimate of a mission-valued world model



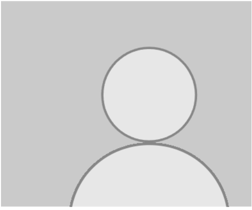
Basic Data Fusion Definitions
Data

- ***Data*** are content with no meaning, e.g., 1001101

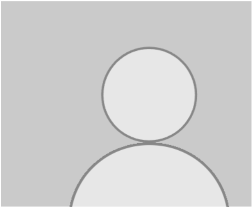
Data upper	Implied Radix	Data lower	Data Type	$(\text{value})_{10}$
100		1101	ASCII	"M"
100		1101	Binary magnitude	+77
100		1101	Integer	-51
100	•	1101	Fixed Pt	+19.25
100	•	1101	Signed Floating Point	-12.75

- "Data are 'individual observations, measurements, and primitive messages [which] form the lowest level. Human communication, text messages, electronic queries, or scientific instruments that sense phenomena are the major sources of data.' " [Waltz, 9]

Basic Data Fusion Definitions
Observation, Sensor, Measurement



- ***Observation***: ***one acquisition of data*** containing signal plus noise plus clutter, e.g., measure temperature, image a crowd, count DNS attacks, intercept communications
- ***Sensor: device or process*** that performs observations and which actually acquire data, e.g., RADAR, IR, multispectral, cyber, acquire social media data from a social media platform, query database
- ***Measurement***: ***integration of multiple observations*** to improve signal to noise ratio (SNR) or extract signal from clutter to produce an estimate, e.g., integrate independent radar observations to improve SNR, quantify DNS attack rate, correlate data from multiple databases



Basic Data Fusion Definitions Information, Knowledge

- ***(Generalized) Information**: **change in uncertainty***, e.g., reduction of variance of a random variable of interest; Kalman filter state estimate; differentiate terrorist members from group; physically locate cyberthreat
- ***Knowledge: information once analyzed, understood, and explained***, e.g., a Bayesian Net (BN) is a probabilistic knowledge repository; a disease diagnosis; a list of known terrorists; particular malware used to infect computer

Introduction to Sensor Management, © K. Hintz

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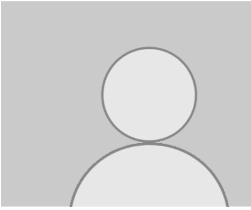


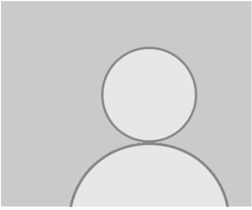
Basic Data Fusion Definitions

Intelligence, Surveillance, and Reconnaissance (ISR)

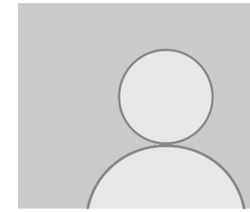
[Sims & Gerber, 10] “... intelligence is best defined as the ***collection***, analysis, and dissemination of ***information on behalf of decision makers*** engaged in a competitive enterprise and that its performance can be judged according to some relatively simple measures."

[Sims & Gerber, 11] "Decision makers matching wits with an adversary want ***intelligence—good, relevant information*** to help them win. Intelligence can gain these advantages through directed research and analysis, ***agile collection***, and the timely use of guile and theft."

Basic Data Fusion Definitions
Situation Assessment *vs* Awareness

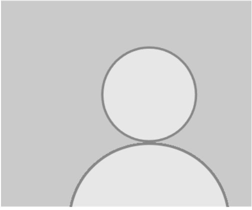


- Situation ***assessment*** is the "…estimation and prediction of relations among entities, to include force structure and force relations, communications, etc." [Blasch *et al*., 12]
  - **Search**: What processes (physical or human) are in the environment
  - **Track**: What is the current physical state of the process
  - **Identify**: Who or what is the process; classifying can improve state estimation, e.g., is it is fighter or a helicopter?
- Situation ***awareness*** is . "… a fusion problem involving the identification and monitoring of higher-order relations among level-one objects." [Matheus, *et al*., 13]
  - ***Why*** is the process in the environment?
  - What are its ***intentions***?



Motivation for Sensor Management

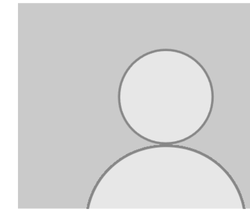
- Need to ***inform situation assessment, not situation awareness***
  - Situation ***assessment***: ***what*** is in the environment
  - Situation ***awareness***: ***why*** it is in the environment and what are its intentions
- Asymmetric warfare requires social sensing (soft sensors), physical sensing (hard sensors), computer network sensing (cyber sensing & SCADA)
- Need to determine ***where to physically locate sensors*** prior to engagements or events
  - Monitoring St. of Hormuz for strategic and tactical sensing
  - Situation assessment of Superbowl environment before and during event
  - Natural disasters such as hurricanes for post impact damage assessment
- Ubiquitous internet of things (IOT) has ***bandwidth constraints***



Basis And Need For Sensor Management

- Sensor management is a methodology for selecting and ***utilizing the best sensor or combination of sensors*** to meet some performance index
  - A stochastic optimization problem
- Performance criteria for situation assessment
  - Maximize information while ***reducing data quantity***
  - Observe processes ***relevant*** to our situation
  - Observe processes in a ***timely*** manner
  - Order observations based on mission ***value***
  - Order observations based on ***probability*** of obtaining desired information
  - Operate in ***real-time***

Introduction to Sensor Management, © K. Hintz



SM is a Constrained Optimization Problem

- Sensors ***cannot observe in all directions at the same time***
  - Increase range capability at expense of instantaneous field of view

- Sensors ***cannot use all modes simultaneously***, e.g., search *vs* track *vs* ID
- Sensor platforms have ***limited computation capability***
  - On-board with reduced communications requirements
  - Off-board with increased communications requirements
- Tradeoff between ***accuracy and timeliness*** of measurements
  - Longer dwell times improve SNR but target may have already accomplished mission

Sensor Capability Comparison by Type*

Sensor Type	Geolocation Quality	ID Quality	Field of View	Target Motion
ELINT	Poor-medium	Good Emitter	Wide	Typically Stopped
COMINT	Poor-medium	Medium	Wide	Both
MTI	Good		Medium	Moving
SAR	Good	Medium	Medium	Stopped
IR/EO	Good	Good	Narrow	Both
ACOUSTIC	Medium	Medium	Narrow	Both

*[Hanselman *et al.*, 25]

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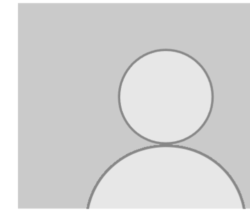
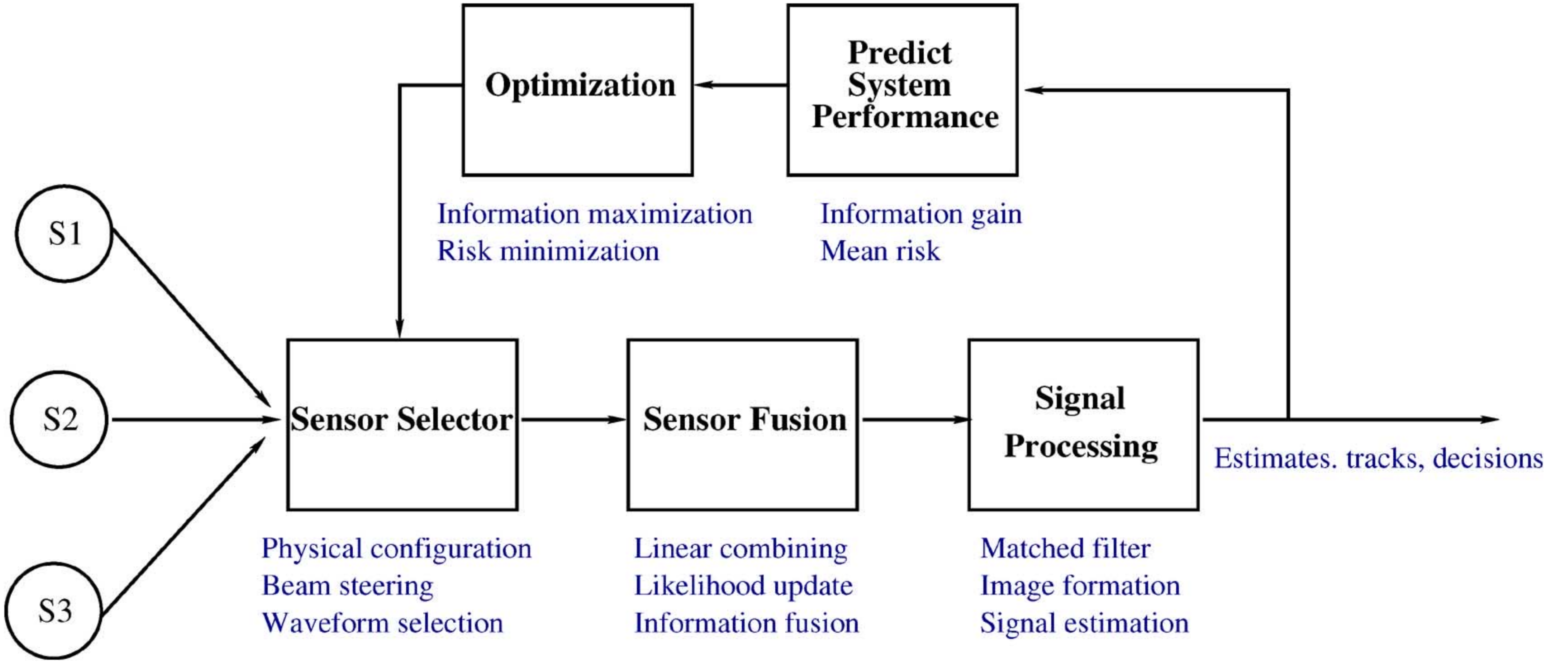


Big Data Problem

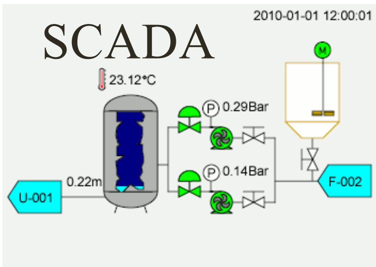
- Big data results from collecting data ***without regard to its information content***
- Sensors are in a ***data rich, information poor*** (DRIP) environment
- Big data problems, the 4 V's
  - **Volume**
  - **Variety**
  - **Velocity**
  - **Veracity**
- Sensor management can ***reduce the quantity and increase the quality*** of the data by orchestrating the sensing resources to collect primarily those data which are most ***informative*** and most ***valuable*** to the mission

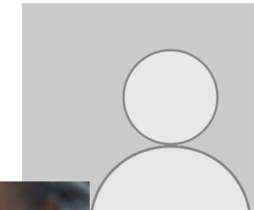
Essential Components of a Sensor Management System*



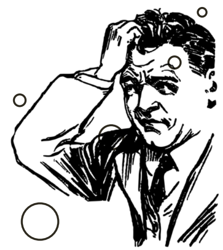
*[Hero et al., 26]

Generalized Sensor Manager Issues



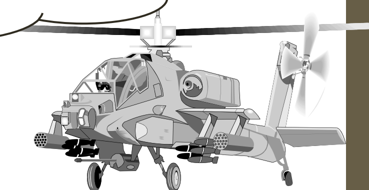


Search: Is anyone else out there?



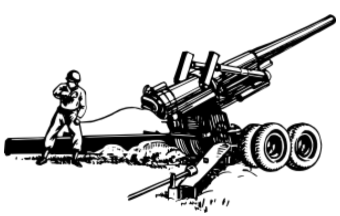
Track: Who should I track ?

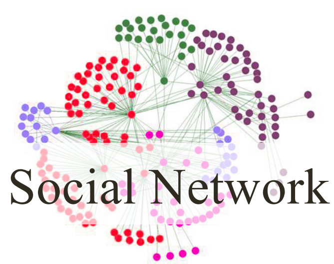
Identify: Who is it?



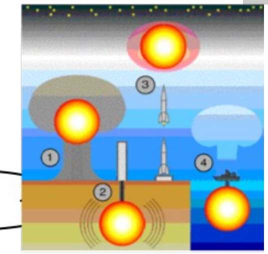
Value: What is the most important mission information?

Constraints: What is the best way to find out?



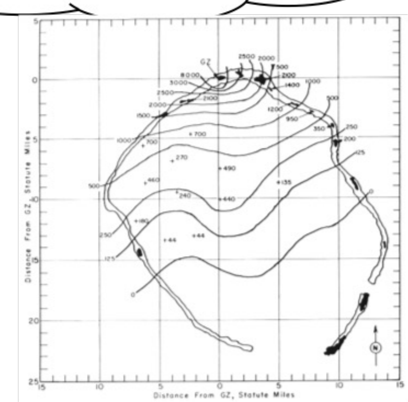


Particular Issues for Nuclear Incident



Identify: What type of nuclear event occurred?

Predict: What will be the area affected?



Track: Which way is the radiation cloud moving?

How: Which sensor can acquire a timely, accurate gamma ray count?

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http://www.archives.gov/education/lessons/fallout-docs/images/atomic-cloud.gif
http://www.radmeters4u.com/cdv715-new.jpg
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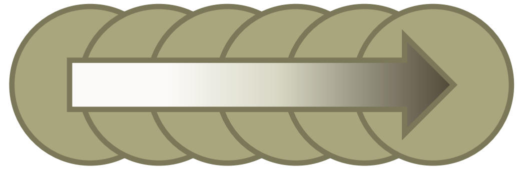
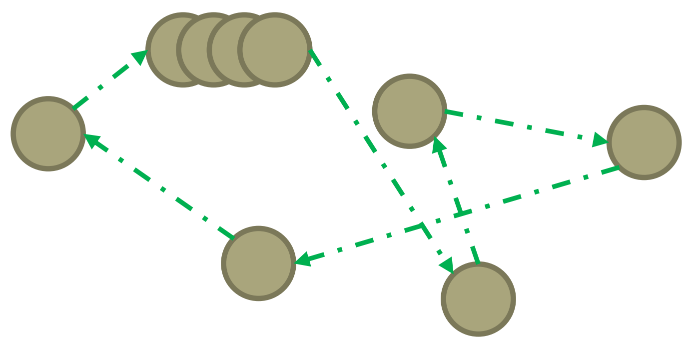
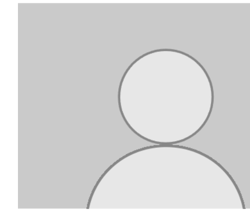
Scheduler *vs* Manager: Performance Index



- Sensor ***scheduler***
  - Determines the sequence and type of observations to make within the constraints of ***sensor capabilities*** once it has been decided which entities to observe
  - ***Myopic*** performance index, e.g., search the entire volume in a fixed amount of time, track all detected targets with specified uncertainty
  - ***Perform assigned tasks without knowing why***
- Sensor ***manager***
  - Determine which observations sensors should make in order to ***best meet mission goals***
  - ***Global*** performance index





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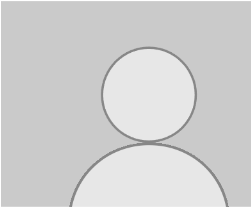
Scheduler *vs* Manager: Scope



- Single sensor does not have the ***big picture***
  - Need to use ***fused world model*** to direct individual sensor actions
  - The ***context of a measurement*** defines a sensor measurement's contribution to mission goals
  - **A sensor's optimization is not necessarily a mission optimization**
- Single sensor ***cannot observe all sources*** of data so it can only imperfectly observe one aspect of reality

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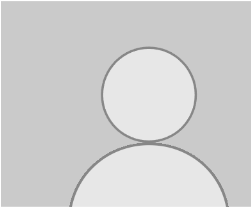
Types of Sensor Systems



- Single platform, single sensor
- Single platform, multiple sensors
- Distributed network of identical single sensors
- Distributed network of identical heterogeneous sensor
- Network of heterogeneous sensors on autonomous platforms operating independently but collaboratively

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Single Platform Sensor Systems

Single platform, ***single sensor***

- UAV with fixed FOV Camera
- Overhead asset

Single platform, ***multiple sensors***

- SPG-51: missile fire control radar antennas
- SPS-52: three-dimensional search radar
- SPS-40: two-dimensional, long range air search radar
- SPS-10: medium range surface search radar

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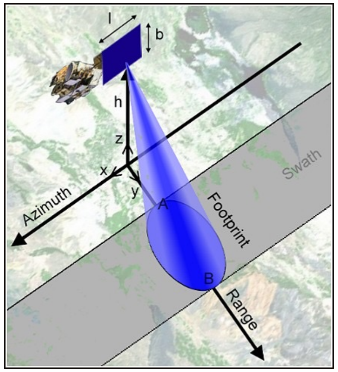
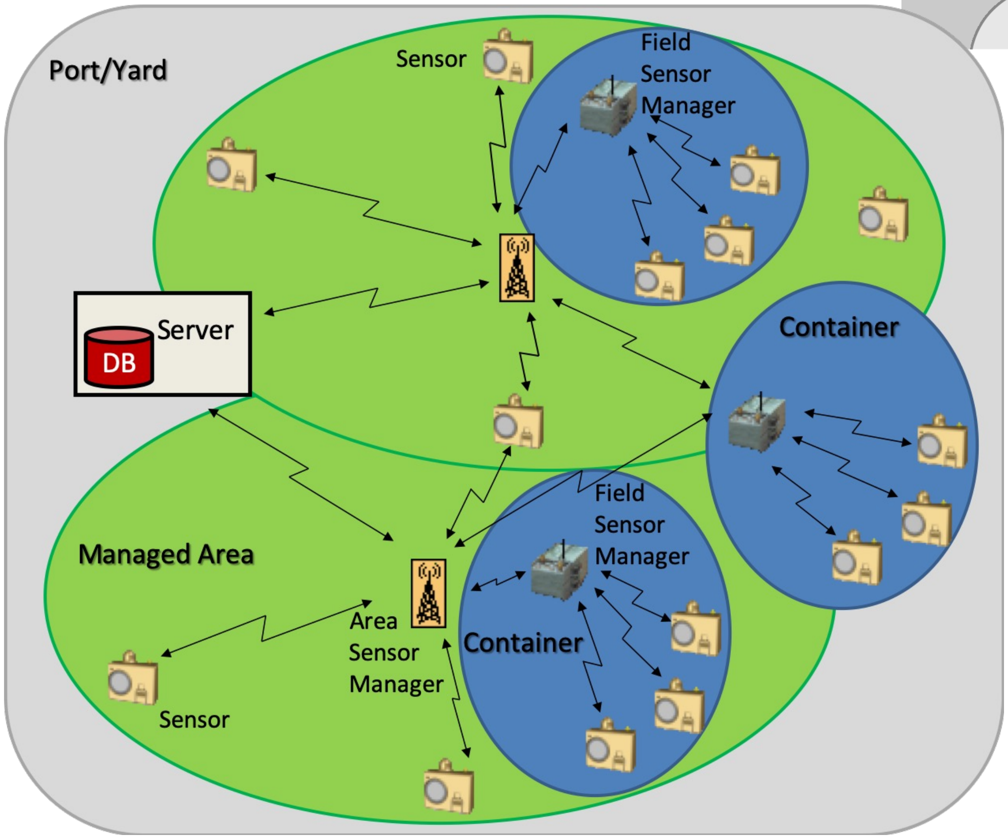


https://commons.wikimedia.org/wiki/Radar#/media/File:Rardiagdrp.jpg

Ad Hoc Network of Homogeneous Sensor Systems Over Small Area

Multiplatform ***network of identical sensors***

- Unattended ground sensors for monitoring containers in field
- Each sensor contains:
  - Passive infrared (PIR)
  - Magnetometer
  - Seismic
  - Vibration



Network of Heterogeneous Electrical Power System Sensors Distributed Over a Large Area

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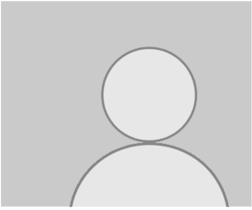
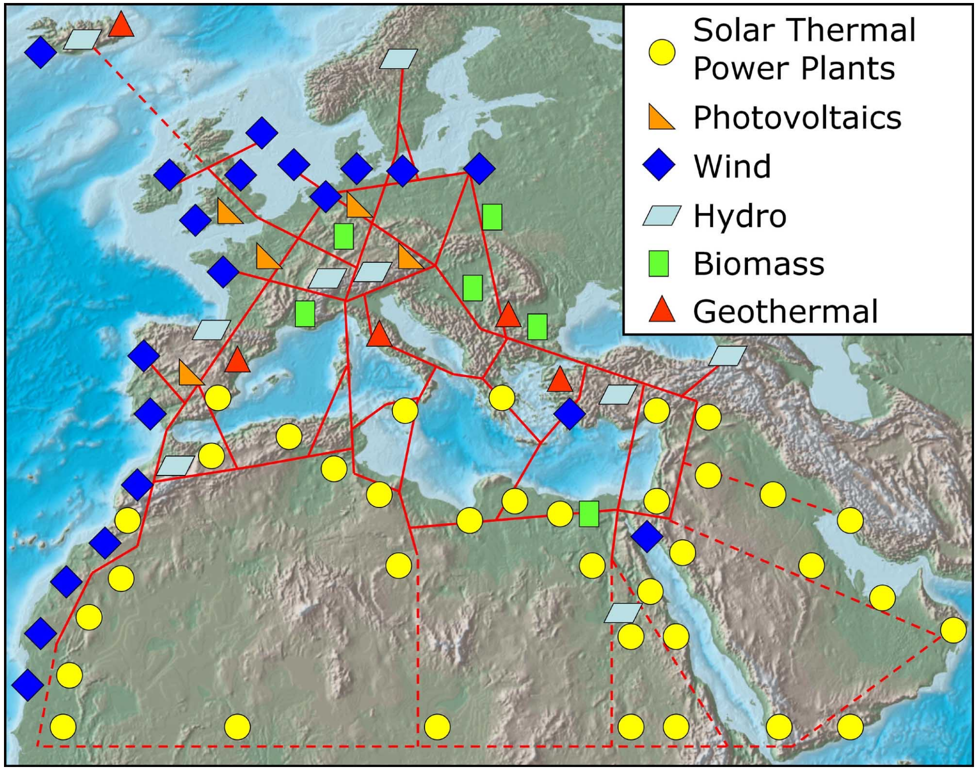


- ***Highly distributed*** energy generation network
- Network is distributed over ***large area***
- Links have different ***bandwidths*** and ***delays***
- Different sectors have different information ***needs***
- Information from different sectors have different, non-stationary ***costs***

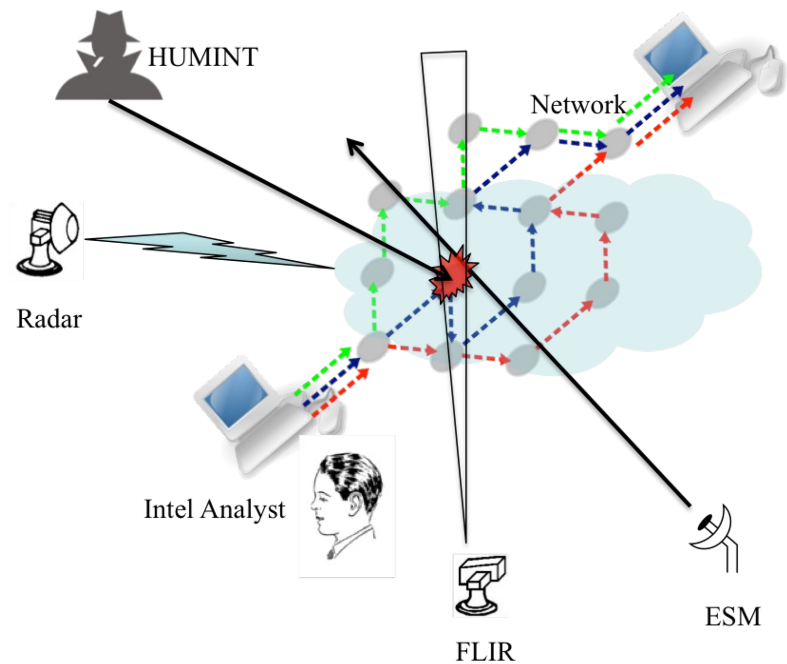


https://commons.wikimedia.org/wiki/File:TREC-Map-en.jpg

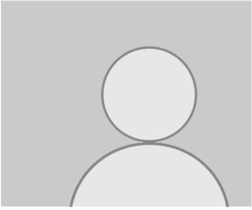
Distributed Multiplatform Heterogeneous Sensor Systems

Multiplatform network of heterogeneous sensors

- Hard sensors (physical data)
- Soft sensors (human generated)
- Social sensors
- Cyber sensors
- SCADA
- Pseudo-sensors



Point Solutions Are Not The Answer



- Point solutions are ***unique to an environment and the set of sensors*** and are not generalizable
- Point solutions are designed to
  - Control one sensor system
  - Operate in one environment
  - Estimate the state of a single process, e.g., a chemical plant
- Limited to observing a complex, nonlinear, dynamic process that is ***well defined and confined***
- Can be observed with a ***fixed, preplanned*** sensor management system
- Designed to meet the bandwidth and accuracy demanded by the control algorithm and the process dynamics

Desired properties of SM system

- The immediacy and complexity of an ***evolving, dynamic, integrated world*** precludes a point solution and demands a sensor management system which is
  - Flexible
  - Adaptive
  - Automatically reconfigurable
  - Indirectly controlled utilizing real-time mission goal management
  - Scalable

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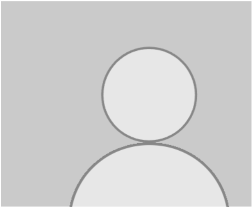
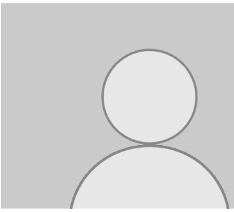
Desired properties of SM system

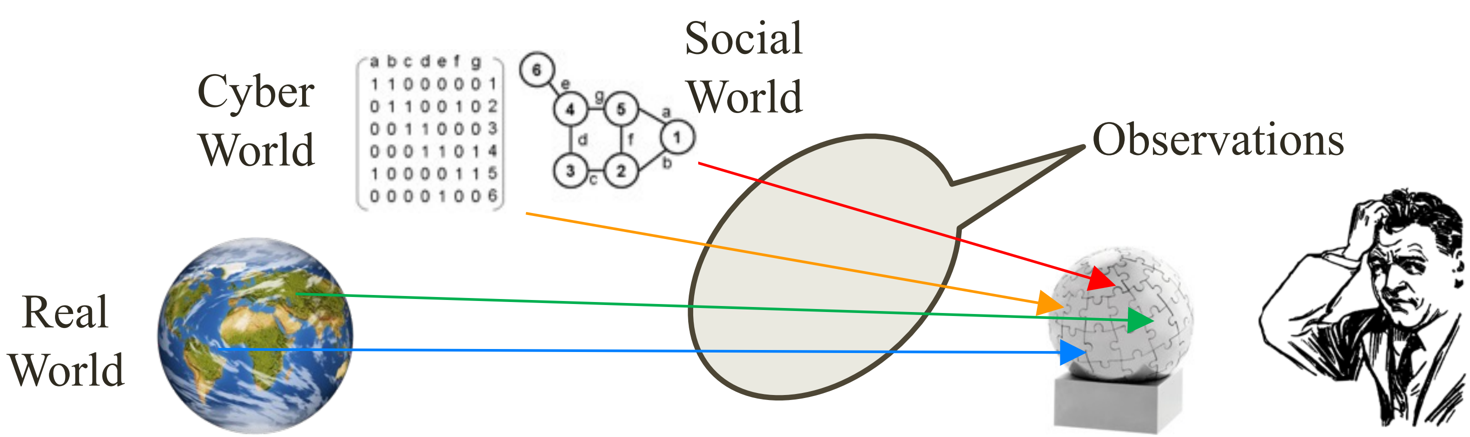


- Need to manage sensing observation ***functions*** and schedule them among the ***capable and available sensors***
- Incorporate sensor ***route planning or repositioning*** within the sensor function management
- Incorporate relative ***mission goal value*** in determining the ***best next collection*** opportunity
- Universal performance index

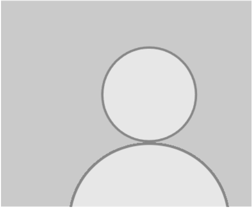
Reason for a Sensor (System)



- ***Information***, not data, is the *raison d'etre* for a sensing system
- More importantly, ***mission-valued*** information is the goal
- The purpose of a sensor system is ***the transfer of information from the real (physical, cyber, or social) world to a mathematical model*** of that world



Historical Basis For Sensor Management



Abbreviated timeline of sensor management development

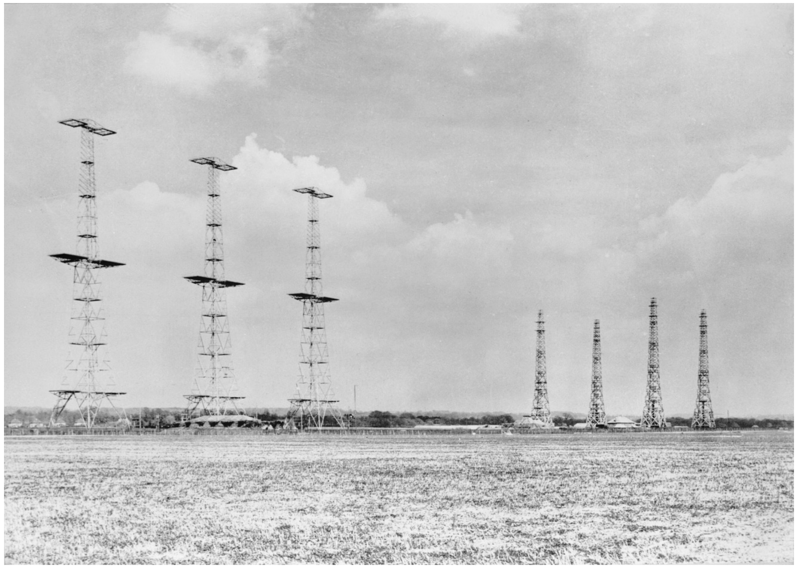
- World War II (WW II)
- Cold War era
- Four coordinated attacks on the United States on 9/11
- Network Centric Warfare (NCW)

World War II (WW II)

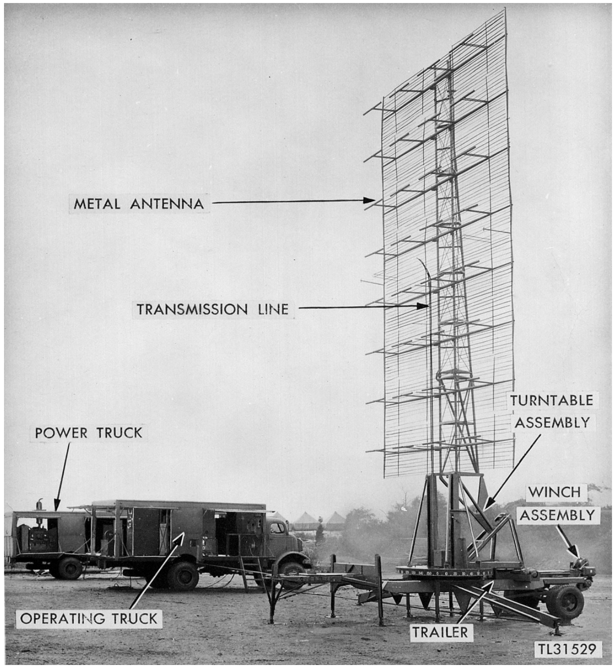
- ***Pre-WW-II:*** the transfer of information from one place to another was limited to
  - line of sight
  - audio landlines
  - radio communications
- ***UK, 1939***: Human coast watchers, HF intercepts, and Chain Home RADARs along the East and South coast of England were integrated to provide significant competitive military advantage
- ***US, 1940***: the raid on Pearl Harbor was detected on a RADAR which was not effectively incorporated into an early warning system, thereby allowing the attack on Pearl Harbor to go undetected until it began

Showed that ***decision makers need an effective way of assessing the situation*** and providing a proper interpretation of the data provided by the sensors

WW-II Radar Stations, Sussex, UK

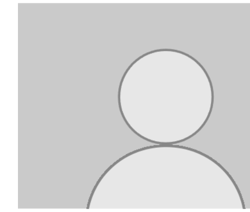


Chain Home : Three transmitter towers, 4 receiver, Sussex, UK



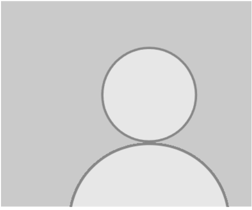
Radio Set SCR-270 @ Opana Point, Hawaii

Cold War Era



- ***Period of geopolitical tension*** after WW II and before the fall of the Berlin Wall and collapse of the Soviet union (USSR) in 1991
- During the cold war, each side's ability to develop effective collection and analytic programs to monitor the other helped clarify intent and discourage strategic war. [Sims & Gerber, 10, 11]
- Development of U-2, SR-71, ***EP-3E***, and reconnaissance satellites
  - ***Integrated multiple heterogeneous sensors on individual platforms*** performing ***local situation assessment*** and technical intelligence collection (ELINT, COMINT, SIGINT)

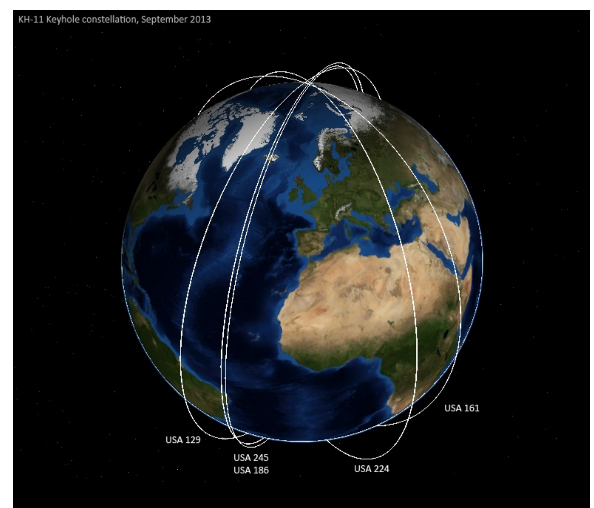
Networks of Sensors

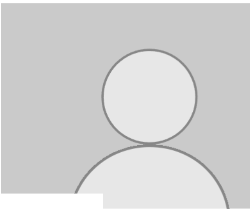


- Development of sensor networks required technologies from four different areas
  - Sensing
  - Communication
  - Computing
  - Control (sensor management)

Beginnings Of Networking: Homogeneous Sensors

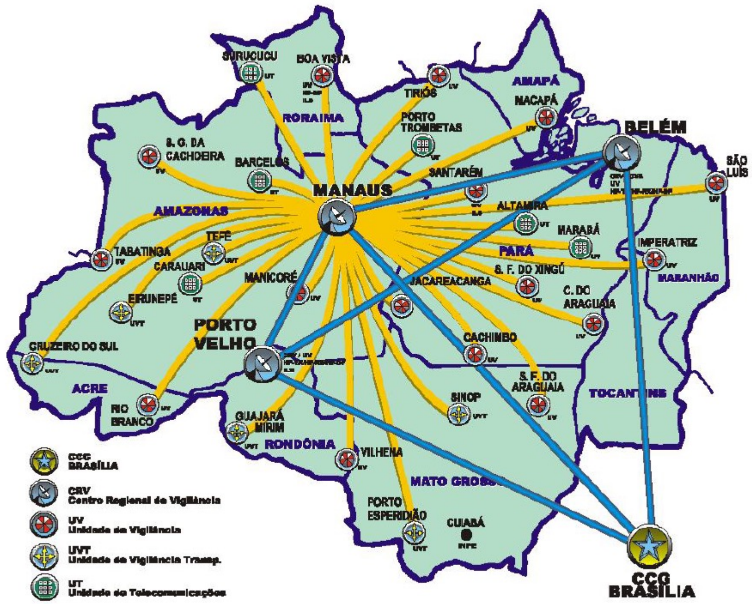
- Sound Surveillance System (SOSUS), 1950s
  - Real time analysis of underwater sound
- Keyhole family of photo reconnaissance satellites, 1960s
  - Vertical integration: collect, analyze, plan next mission
  - Time consuming orbit changes to meet needs
- Air Traffic Control radars, 1960s
  - Cooperative tracking w/ IFF transponder
- National electric power grid: SCADA, 1970s
- Landsat photo satellites, 1980s





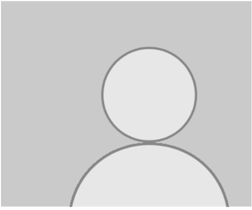
SIVAM, Civilian Network of Heterogenous Sensors*

- SIVAM: ***System for the Vigilance of the Amazon***
- Largest fully integrated remote monitoring system in the world supporting environment controls and law enforcement over land, air, and water resources
- Fully operational since 2005



* [Ferraro *et al*., 27]

Beginning Of Modern Sensor Management

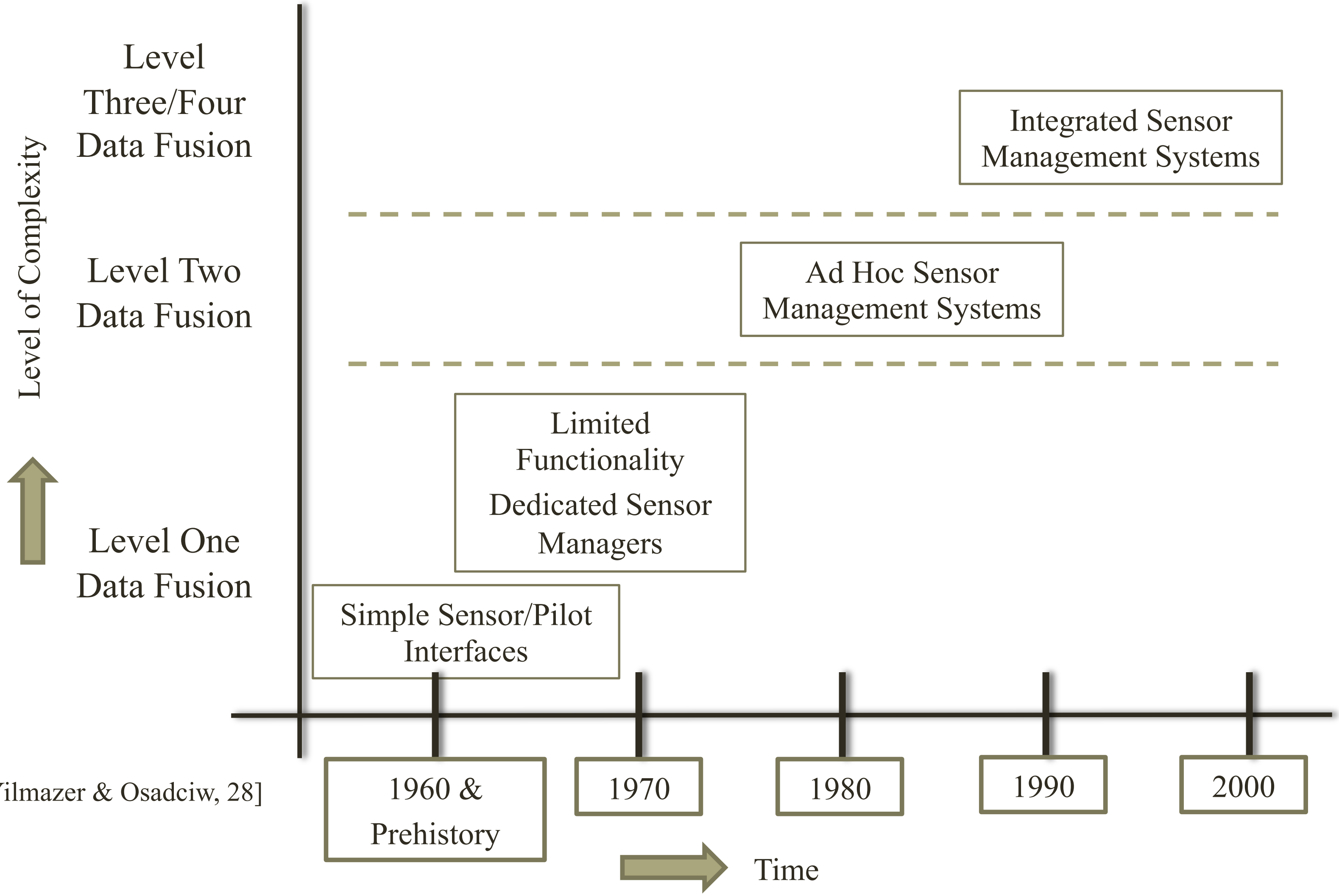


- ***Recognition of the limits of human control*** of the sensors in a sensor suite
  - Too many sensors
  - Too agile for a single person to use effectively
  - Too many other activities, e.g., flying a fighter aircraft.
  - ***Human in the loop*** (HIL) constrained by the bandwidth of the human operator
- Next step was preset beam pointing and frequency agility predicated on a particular mission or expected encounter with an adversary
  - ***Still sensor scheduling***, not management

Introduction to Sensor Management, © K. Hintz

Timeline of R&D in SM *

Increase in complexity, but no evolution of a general, underlying theory



* [Yilmazer & Osadciw, 28]

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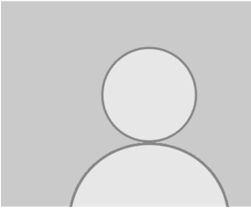


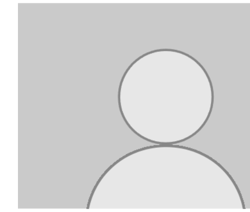
September 11, 2001

- Four coordinated attacks on the United States
- Need to rethink sensor management in the area of ISR with the emphasis on intelligence, surveillance, and reconnaissance being ***enabling technologies that support situation awareness***
- While much intelligence is collected in the battlefield at fairly low levels for local and immediate purposes, ***intelligence is generally understood*** as

  …the collection, analysis, and dissemination of information on behalf of national security decision makers. ***Decision makers*** are, by this and almost any other definition, ***integral to its function.*** [Sims, 14]

- Emphasis shifted to including ***social media and HUMINT***

Vacuuming Communications Networks



- **DRIP**: We can no longer just collect unprocessable amounts of data from military sensors, world news media (OSINT), intercepts of adversary communications (COMINT), social media postings, public service band communications, or cyber sensors hoping to find the needle in the haystack
- Need to emphasize the decision maker's ***immediate intelligence needs*** and utilize the best resource to obtain that intelligence
- What is needed is valued and timely ***knowledge***, i.e., ***actionable intelligence***

Design Consideration: HOL rather than HIL

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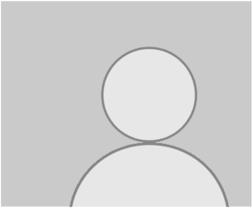
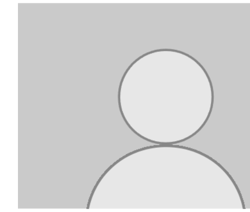


- The complexity and speed of modern sensor systems is such that it is not effective to have a ***human-in-the-loop*** (HIL)
- A ***human-on-the-loop*** (HOL) can produce a more effective solution if an ***indirectly controlled***, closed loop system is designed with a proper measure of performance
- From the human's perspective, there are topmost mission goals which are not related to one another by an inclusion relation so the ***human's topmost mission values must be distributed among them in a zero-sum game*** (*e.g.,* aviate, navigate, communicate…hierarchical task model)
- Included mission goals are not directly valued by the human but accrue value from their contribution to higher level goals
- A ***goal lattice*** (GL) effectively implements this indirect HOL control
- The human tells the IBSM system the relative mission value of ***what he wants*** rather than ***how to obtain*** it.

The Changing Roles Of Battlespace Entities*



- Network Centric Warfare (NCW)

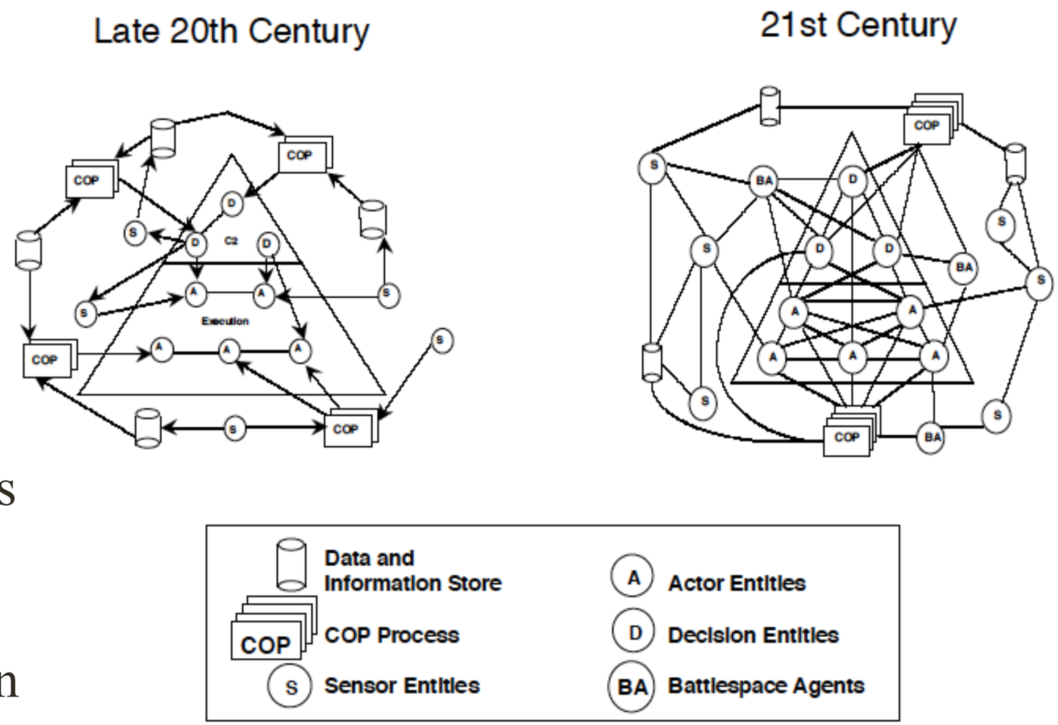


Figure 17. Roles of Battlespace Entities

- ***Modern sensor management***: sensors are viewed as ***providing a situation assessment*** rather than platform specific data

* [Alberts, *et al*., 15]

Underlying Principle of Network Centric Warfare (NCW)*

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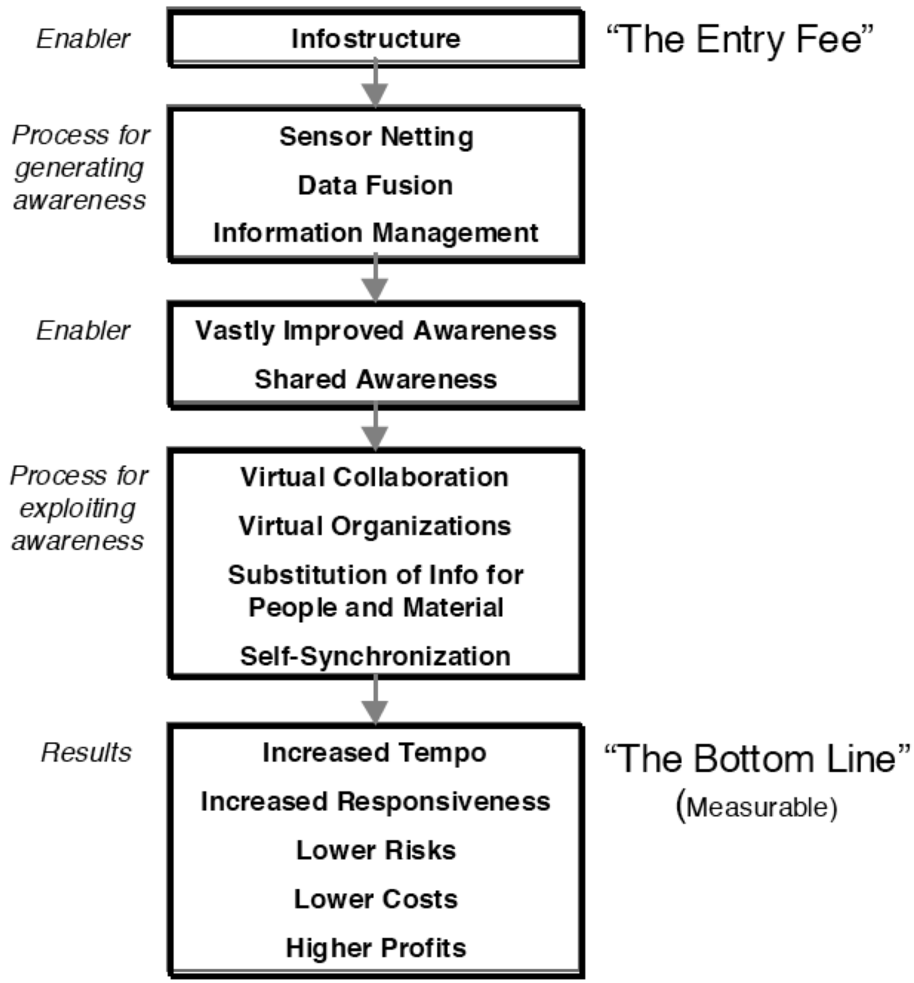
"The ability of a competitive ecosystem to generate and exploit ***competitive awareness*** (an awareness of one's competitive domain or competitive space) has emerged as a key enabler of effective decision making and a principle component of competitive advantage in multiple sectors of the economy"

* [Alberts, *et al*., 15]

The Network-Centric Enterprise *



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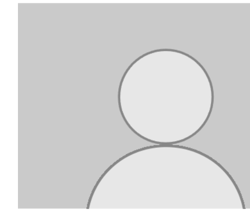
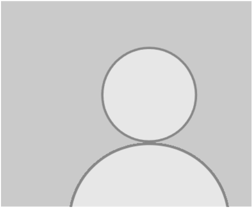
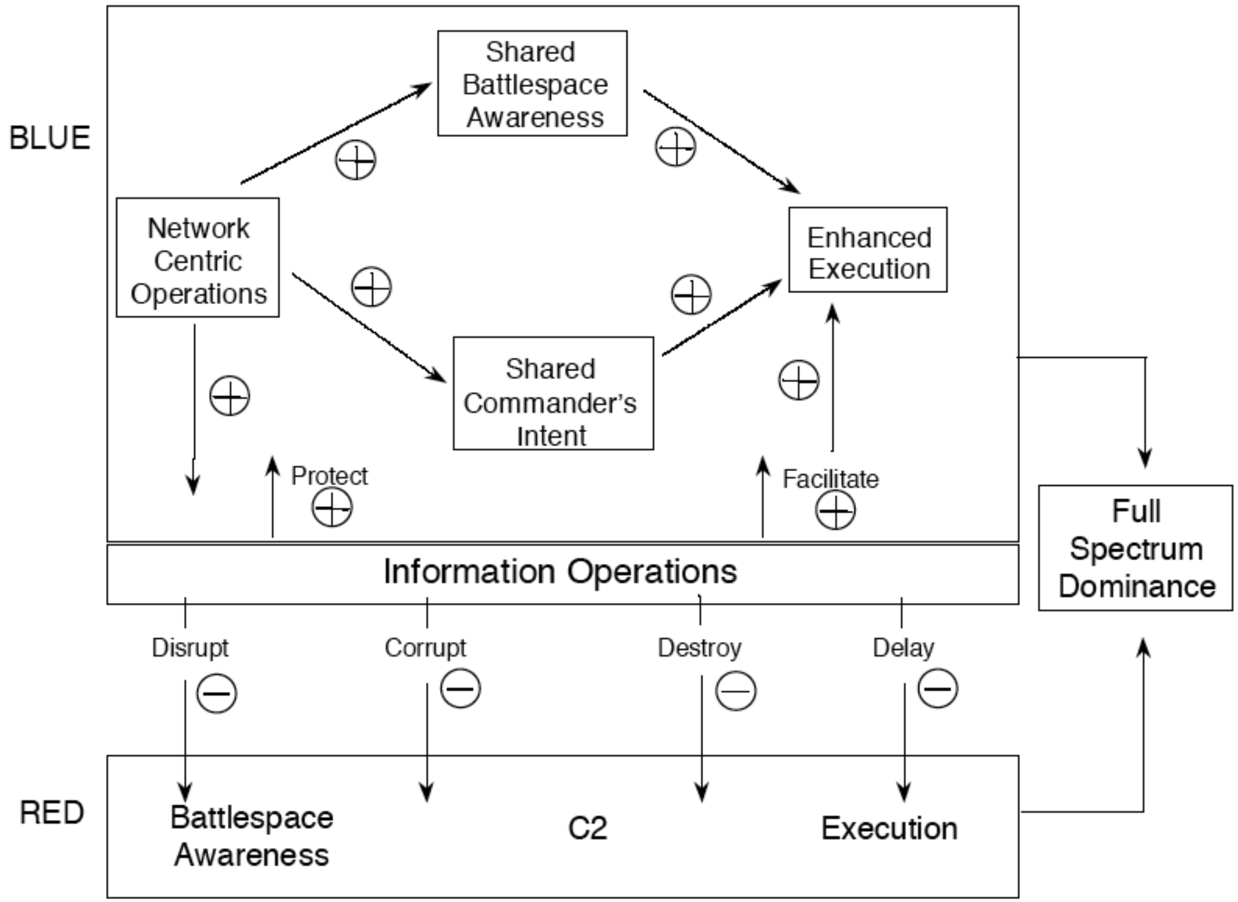




Information Centric

- ***Platform is not important, the data which it provides is***
- Actual use of a sensor must be valued based on its ***contribution to a mission***, not merely the platform on which it resides
- ***Insufficient bandwidth*** to broadcast all observations
- ***Inadequate number*** of sensors to collect needed data
- Need to shift from ***data push*** to ***data pull*** where the network is only used to transfer valued, timely information producing data
- Some of the information is judged to be valuable to all participants and this can be posted in an easily accessible network location, e.g., blackboard
  - These data are kept up to date with a background process which utilizes sensors when they are not being utilized for more mission valuable tasks

NCW Full-spectrum Dominance Enabled By Information Superiority *



* [Alberts, *et al*., 15]

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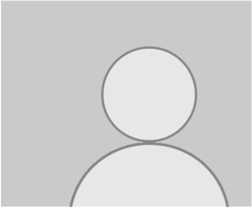
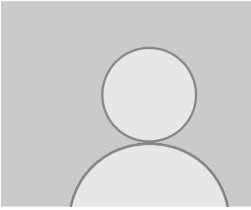


Modern Conflict

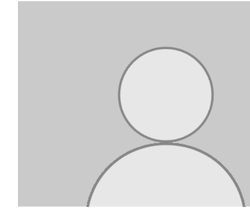
- The ***asymmetry*** of the relationship between the ***adversaries and the US military*** leads to the inevitable conclusion that the sensing of the physical world is no longer enough to counter the threat and we must include the integration of hard (physical measurements), soft (generally considered to be human produced data), and cyber sensors.
- Sensor management is **not directly concerned** with data fusion and information extraction, but the topics can't be ignored…**SM is an enabler of better data fusion and information extraction**

Macro issues in Sensor Management



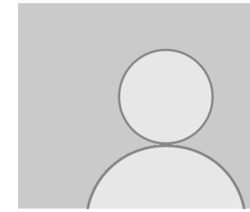
- Political issues
- Resource constrained
- Multidisciplinary
- Competing users
- World models

Sensor Management Political Problems



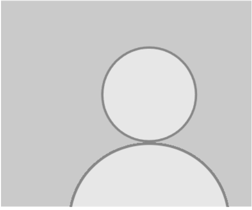
- ***Conflicts*** between ***owners*** of sensors and ***needers*** of the data that owners can provide
- Multiple agencies need the sensors to collect data, but ***no effective way to adjudicate*** among the values of those requests
- Conflict between operational ***tactical*** needs and policy driven ***strategic*** needs
- ***Micromanagement*** of sensor selection and usage by the ***needers*** of the data to the detriment of the effective use of the sensors to meet all needs…***need to specify quality and timeliness of data (e.g., NIIRS #), not sensor***

Sensor Management Breadth Problems



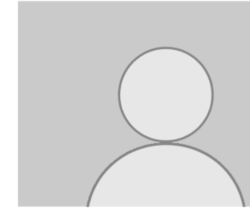
- SM is a ***multidisciplinary*** problem
  - Electrical engineers
  - Communications engineers
  - Operational research
  - Subject matter experts (SME)
  - Intelligence analysts
  - Social scientists
  - Mathematicians
  - Computer scientists
  - System engineers
- Leads to a need for an ***ontology*** for communications and transfer of design information among all disciplines
  - Example is hardware description languages (HDL) in computer engineering

Sensor Management Feasibility Problems



- Scalability
  - ***Point solutions don’t scale well***
  - ***Computationally unfeasible*** as number of platforms and/or sensors grows
  - Some mathematical methods have unbounded growth, e.g., multi-hypothesis tracking
- Emission control (EMCON)
  - ***Avoid detection***
  - ***Mode selection*** to minimize probability of own detection while still making useful observation
  - Active low probability of intercept mode or passive sensing
  - Flight path planning to avoid detection utilizing $\frac{1}{R^4}$ losses for adversary radar
  - Passive pseudo-sensors for fixing targets while EMCON

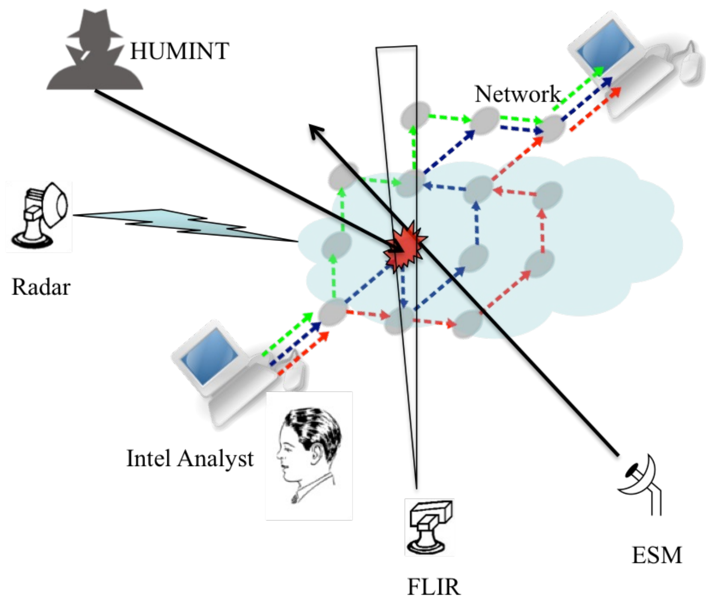
Sensor Management Integration Problems



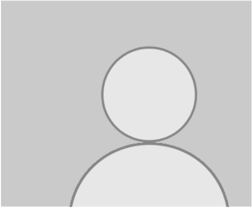
- Fusing of ***non-contemporaneous measurements***
  - Need to ***extrapolate observations*** by different sensors to a common time before fusion
  - Need to decide whether to ***extrapolate forward or filter backwards*** before fusing
- Virtual Sensors
  - Reconfiguration of a single sensor in real-time by changing operating waveforms, modes, frequencies, or beamforming
  - Some sensors adapt automatically to observations
  - ***Need to define a sensor by its functions, not its physics***

Sensor Management Non-commensurate Data Problem

- Heterogeneous
  - Different physical or social domains with different accuracies and uncertainties
  - Physical data signal processing is quite fast compared with the natural language processing
- Pseudo-sensors
  - Define a function as the ***simultaneous observation by two or more independent sensors***
  - Insures contemporaneous measurements
  - Waits for ***contemporaneous availability*** of sensors
  - Pre- or post-detection fusion

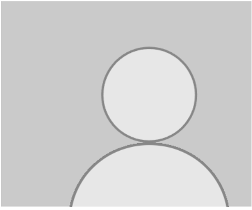


Design Considerations: Orthogonal Definitions & Decomposition



- Many sensor management systems (SMS) are ***ad hoc*** spaghetti diagrams of interconnectedness such that they ***do not admit of piecewise improvement***
- A decomposition of the sensor management system concept into ***orthogonal components with well-defined interfaces*** among them allows for evolution and an increase in component complexity without increased system complexity
- Designing the components as transfer functions with well defined *goes-inta*'s and *goes-outa*'s ***enables evolutionary replacement of a component*** with a newer, faster, or higher fidelity approach to performing that function without disrupting the entire system
  - This is an approach similar to VHDL with entities and architectures or **C** with function prototypes and function definitions
  - Allows for build-a-little, test-a-little as well as co-development of components

Design Considerations: Probabilistic world model



- Observing the physical or meta-physical world through ***physical, social, or cyber sensors*** is associated with uncertainties in those observations
- There are ***rarely perfect answers*** to questions in a world model which is the result of uncertain observations (due to random measurement or process noise) and the world model must reflect this
- A ***probabilistic world model***, *e.g.,* Bayesian Network, carries with it the uncertainties in the nodes
- A ***causal Bayesian network*** allows for analysis of the effect of some indirect conditional probabilities on nodes of direct interest to the decision maker as well as predictions of changes in the conditioned nodes' certainty with the acquisition or anticipated acquisition of data [Hintz, 16]
- More importantly, a probabilistic model ***enables the computation of the increase or decrease in world (global) knowledge measured as information gain or loss*** which results from changing our uncertainty about a conditional probability in that model [Hintz & Darcy, 17]

Design Considerations: Bidirectional Interfaces

- Interconnecting the partitioned components by bidirectional interfaces allows for ***immediate feedback*** if a request cannot be satisfied and the original request's replacement by an alternative request
- ***No need to wait*** for the entire closed loop system to respond to a request if any intermediate function is not feasible
- This may bubble back up through multiple layers to the originator allowing more immediate ***consideration of alternative information needs***
- This process can immediately inform the requestor of the fact that the ***sensor system is unable*** to obtain the requested information

Short Break

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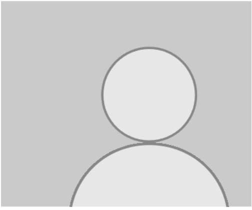

World Models

- Real world
- Mathematical model of world
- Display and presentation of world model to decision maker [not covered here]

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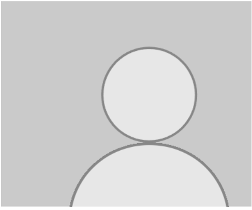
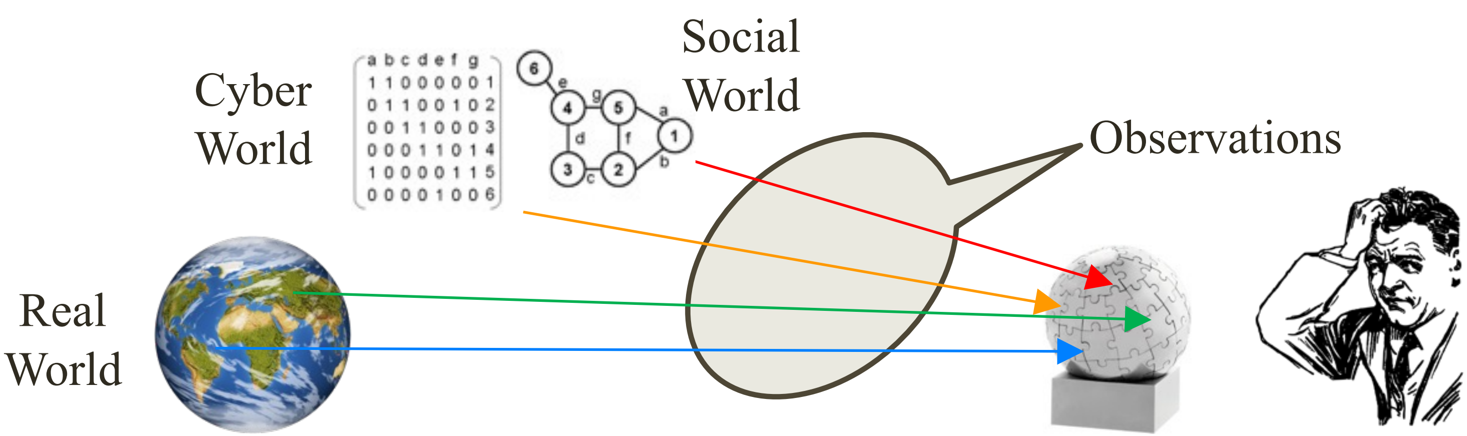
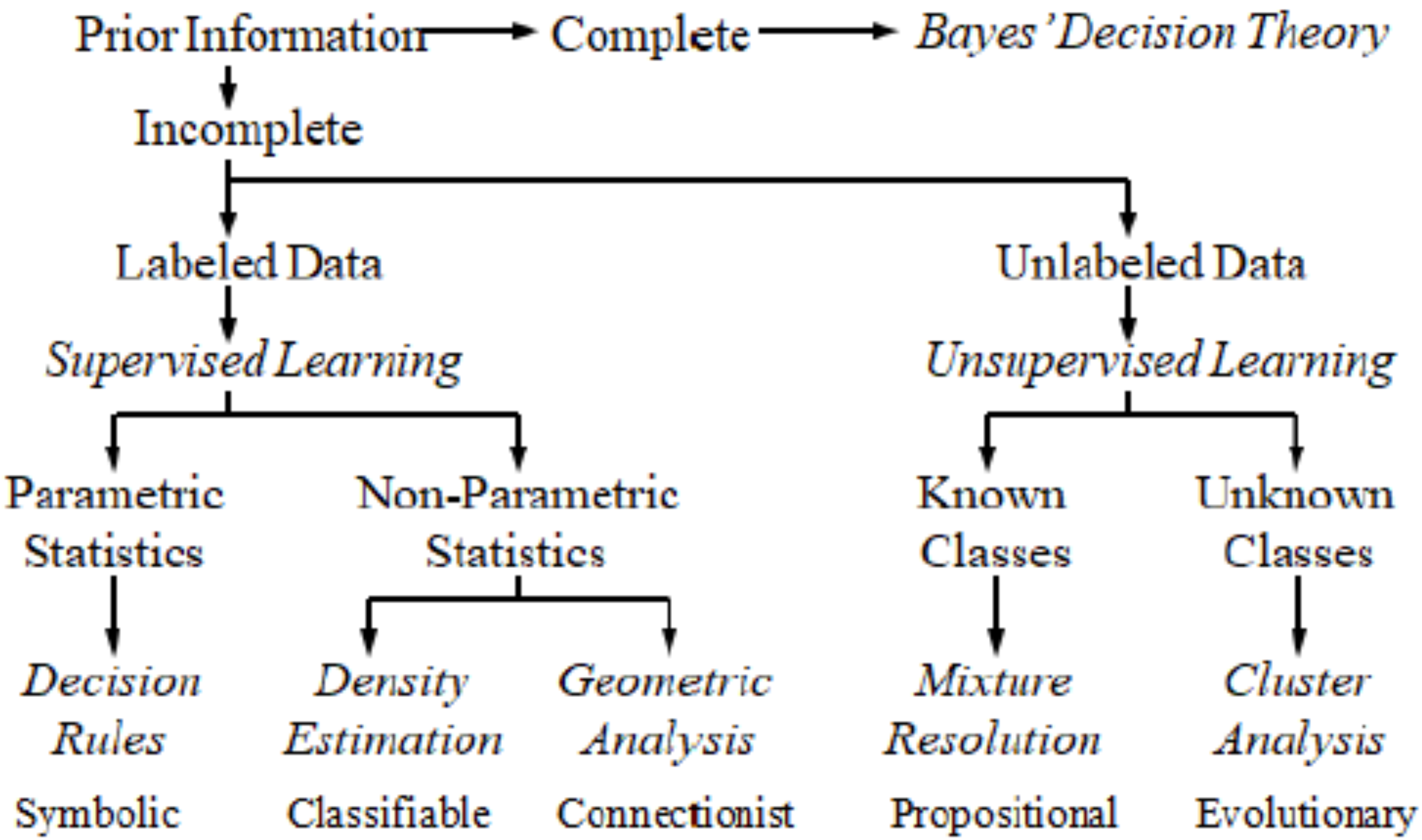
Mathematical Models of the Real World



Decision maker cannot see the ***real world***, but only the ***mathematical representation*** of the real world that results from the combined sensing actions

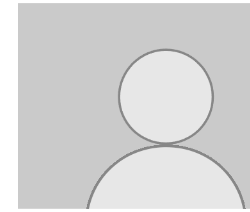


Partitioning Of World Models Based On Amount Of Information *



* [Blasch *et al.*, 29]

Issues with World Models



- Observations of the real world contain ***uncertainties***
  - Additive measurement ***noise***
  - ***Unmodeled*** or uncertainties in process model, e.g., process noise in K-filter, latent variables in Bayes Net
  - Differentiation between ***signal, clutter, and noise***
    - ***Noise*** is usually AWGN with SNR improvement possible over time and/or ERP
    - ***Clutter is real signals*** whose SCR cannot be reduced by an increase in transmitter power or effective radiated power
- After detection, may be desirable to identify target
  - Statistical pattern recognition: feature selection is critical
  - Artificial neural networks: nonlinear mapping, no underlying model
  - ***Identification can improve tracking performance by changing process model***
  - Need training data (with truth data for supervised training)

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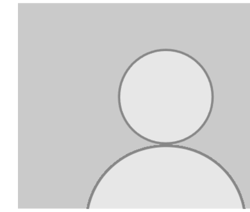
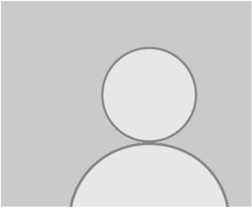
Issues with World Models



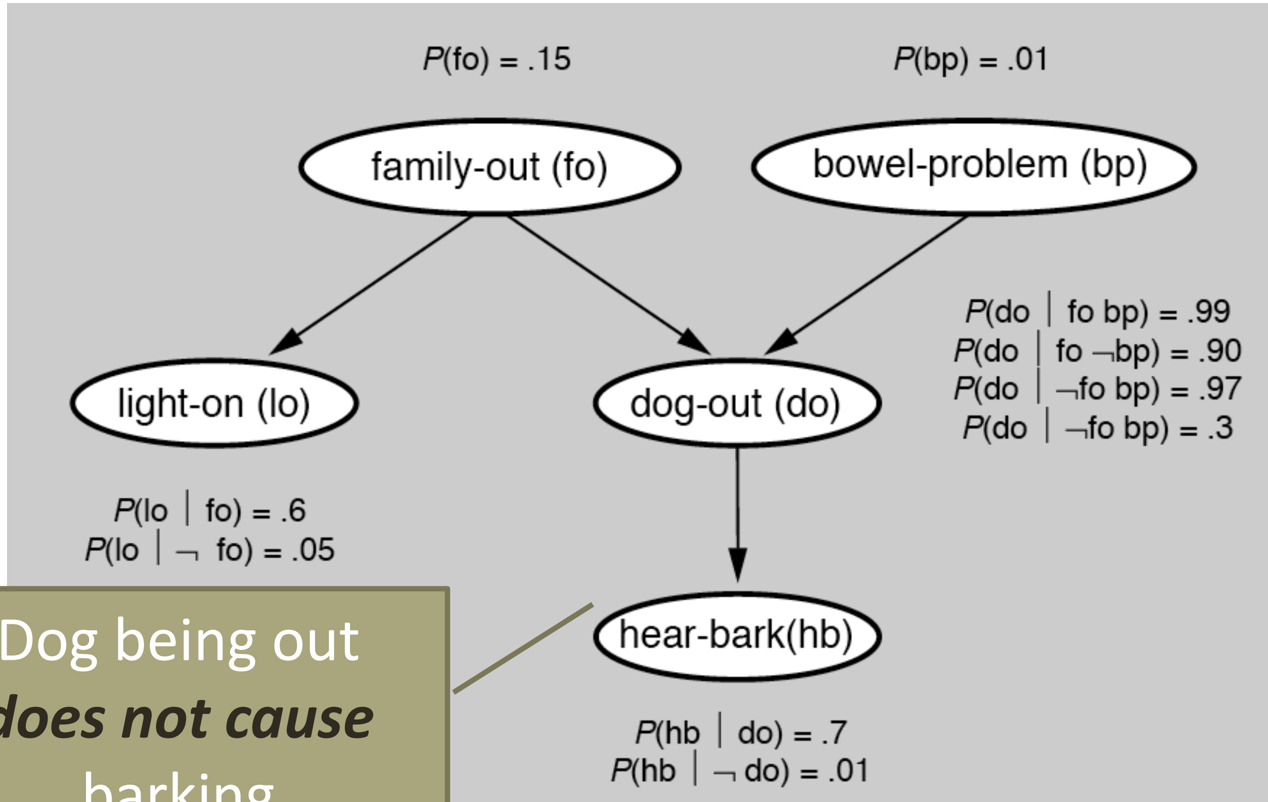
- Unsupervised training if training data not available
  - Big data problem: volume, variety, velocity, veracity
  - Machine learning attempts to find inherent patterns
- ***Context is important*** to understanding observations from two aspects
  - Application domain: same data can be ***processed differently*** based on ***clearance level or role*** of user
  - ***Point of view***: directly observable or inferred from social media

Sensor Independent Probabilistic Models



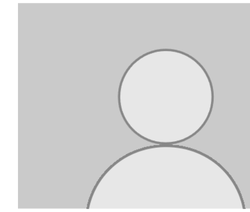
- Evidential reasoning using Dempster-Shafer (DS) belief functions
  - Models the way ***humans assign measures of belief*** to combinations of hypotheses when propositions are not mutually exclusive
- Bayesian nets (BN)
  - Directed acyclic graph (DAG) comprised of nodes and edges showing ***conditional probabilistic relationships***
  - Assigns probabilities to individual hypotheses
- If hypotheses are mutually exclusive, DS becomes equivalent to BN

Example Non-Causal Bayes Net

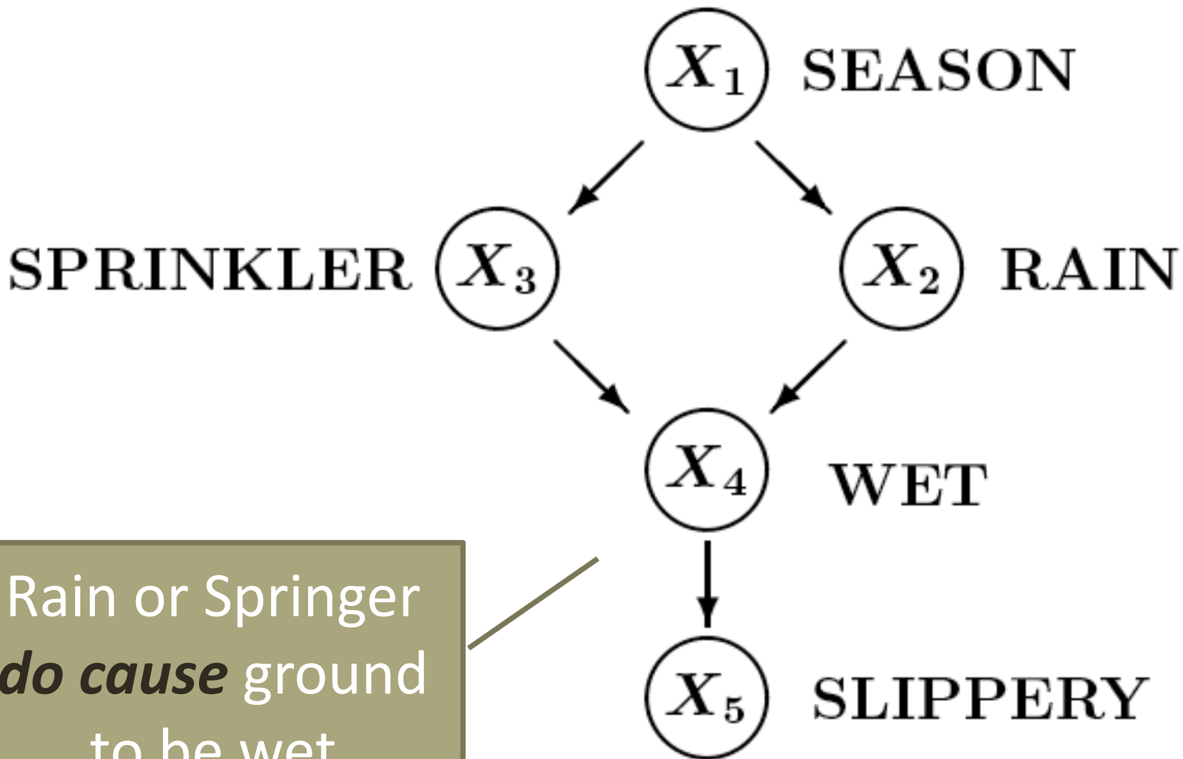


Dog being out ***does not cause*** barking

E. Charniak, "Bayesian Networks without Tears," AI Magazine, pp. 50-63, Winter 1991.



Example Causal Bayes Net



Rain or Springer ***do cause*** ground to be wet

J. Pearl, "Graphical Models for Probabilistic and Causal Reasoning," in Computing Handbook, Third Edition: Computer Science and Software Engineering, Volume I, Chapman and Hall/CRC, 2014.

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Aleatory or Epistemic Nodes

- Nodes of BN are random variables
- Noise associated w/ nodes can be either
  - ***Aleatory***: variability is the natural randomness in a process
  - ***Epistemic***: scientific uncertainty in the model of the process due to limited data and knowledge
- Aleatory nodes ***cannot*** have their certainty improved by additional measurements
- Epistemic node ***can*** have their uncertainty decreased by additional measurements

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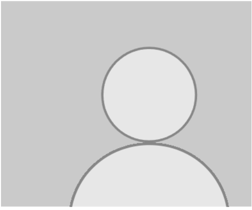


Benefit of Causal BN

- *WRT* sensor management, causal BNs reduce the size of the network to those nodes which are ***causally related*** rather than simply related by correlation
- Causal networks ***do not have to be retrained*** when a configuration in an environment changes
- Nodes can be readily deleted and added by using ***net-frags***
- Causal BNs are extremely useful as probabilistic models of a complex world of interacting physical, social, and cyber entities because they are ***independent of the source of the data***
- ***Temporal BN*** [Hintz & Darcy, 18] enables evaluating alternative choices of sensor function based on future time of observation

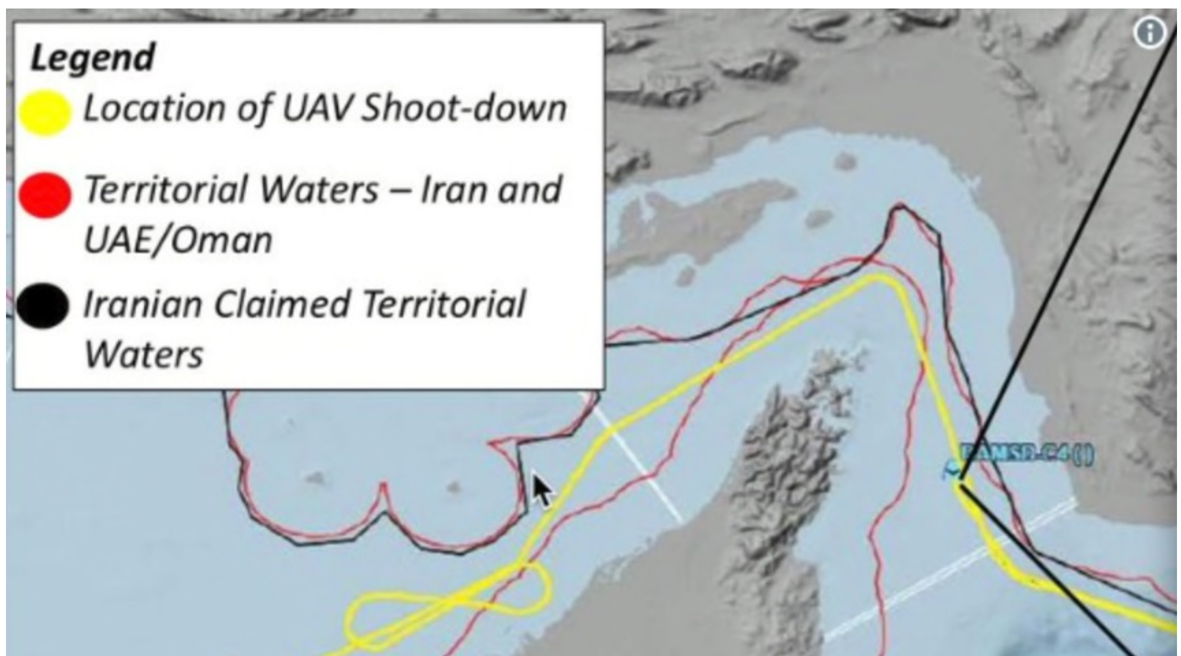
Micro issues in SM

- Route Planning
- Redundant coverage
- Data fusion or decision fusion
- Centralized, distributed, or hybrid management
- Design considerations

Introduction to Sensor Management, © K. Hintz

Operational Issues in Sensor Management: Route Planning

- Best accuracy
- Minimum shielding
- Best probability of observing
- Minimize jamming, clutter, spoofing
- Minimize probability of hostile action
- Communications links
- Maximize information
- Minimize fuel usage



Operational Issues in SM: Redundant Coverage

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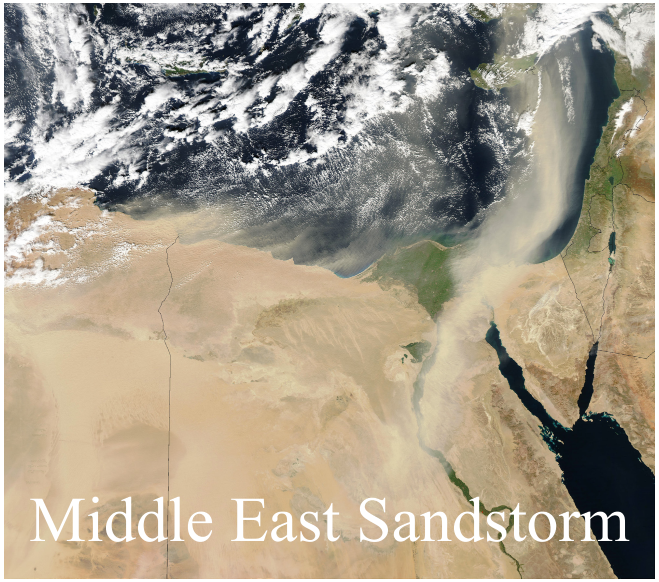
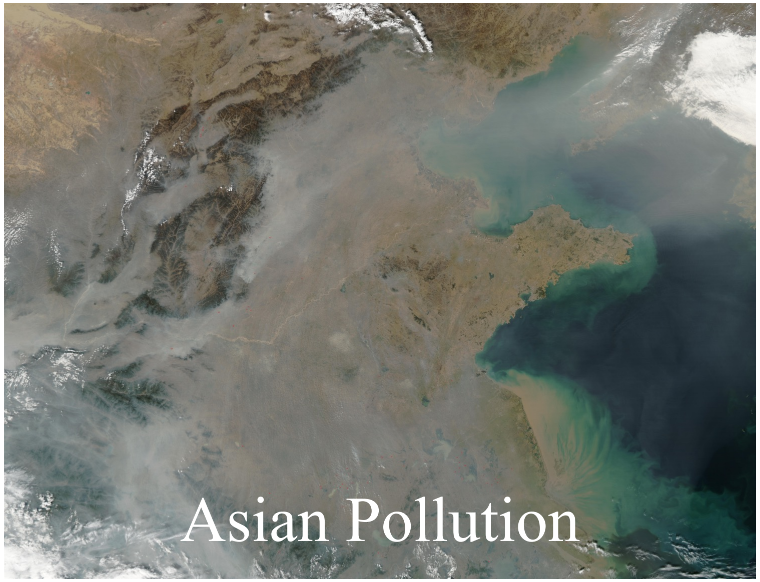
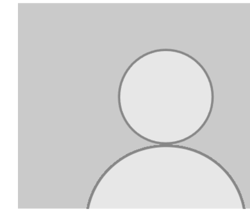
- Oversampling with redundant coverage due to high value of target wastes resources
  - Possibility of obscuration within one sensor platform's FOV may require redundancy provided by independent sensor platform
  - Competing agencies may desire their own data





Operational Issues in SM: Data Fusion



Need for an **internally self-consistent** world representation

- Common coordinate system for merging of data from different platforms
- Data with different accuracies
- Data with different resolutions
- Data association coordinate system errors
- Data pedigree
- Data veracity

Data Fusion: Common Coordinate System

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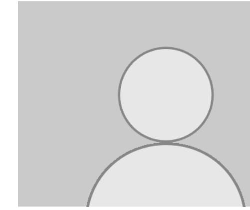
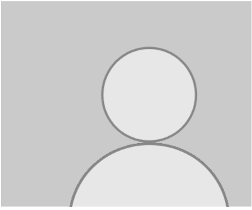


- ***Own platform navigation uncertainties*** translate into errors in the state estimate of targets
- Errors are compounded when fusing data from ***other platforms with navigation uncertainties***
- Sources of platform navigation uncertainties
  - Systemic inaccuracies due to physics involved, e.g., finite beamwidth
  - Random measurement errors, e.g., noise
  - Timing errors
  - Bias errors
- HUMINT errors
  - ***Position and time errors***, e.g., the adversary was in the market at noon
  - ***Observation bias errors***, e.g., person identified as terrorist who isn't

Data Fusion:
Data Association Coordinate System Errors

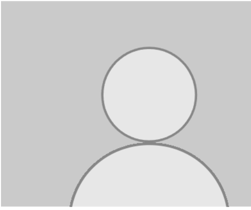


- Data association is a difficult and ***ubiquitous problem*** at multiple levels of the data fusion model
  - Observation to feature assignment in level 0
  - Observation-to-entity assignment in level 1
  - Entity-to-entity association in level 2
  - Situation-to-actor's goals in level 3
- Incorrectly identifying ***crossing targets***
- Persistent surveillance of a moving ground target is interrupted by an ***obscuring phenomenon***, e.g., trees, buildings, or tunnel
  - Loss of track then results in a cost to the sensor system due to need to ***search, reacquire, and possibly reidentify*** the target.

Data Fusion: Data Pedigree

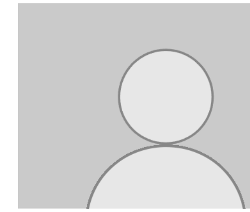
- Data with ***no source identification*** can lead to incorrect situation assessment and incorrect situation awareness (intent of adversary)
- ***Incorrect attribution*** could result in tracking the wrong person
- Pedigree of all data can be used to determine if observations are being ***overcounted*** by being passed through third entity (leads to giving the data more credence than it deserves)
- ***Pedigree must be maintained*** as additional observations are made or related data received

Data Fusion:
Data Veracity



- Data veracity is the measure of trust in the data
- ***Veracity must not be misinterpreted as a measure of correctness***
- Not a measure of uncertainty, but the truthfulness as measured by the conformance with other data and reports
- Global evaluation of the veracity of the event can be computed with outliers being discarded

Data Fusion:
Hard and Soft Fusion



- Data types
  - Hard data: ***physics-based***
  - Soft data: ***human-based***, e.g., reports, social media
  - Cyber data: ***digital*** communications
- Disparate sources of data argue for a common ***ontology for events***
  - ***Synthetic aperture radar*** (SAR) doppler detection and location of vehicles on road
  - HUMINT ***sighting*** of vehicles along with vehicle type
  - ***Cellphone active*** in vehicle

…but data association problem…are they the same vehicles?

Data Fusion:
Hard and Soft Fusion

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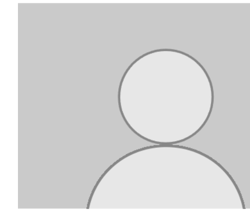
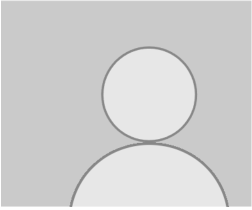


- Data from ***different databases*** with different labels for the same things
  - Different frame of reference
  - Different temporal histories
- e.g., tidal data reported by NOAA is relative to Mean Lower Low Water (MLLW), but land height is recorded with respect to mean sea level (MSL)…3 feet difference in Savannah

Soft Sensor Uncertainties: Target Names, Consistency & Spatiotemporal



- Many-to-one target names
  - Problem: ***More than one identifier for a target*** whether intentional or not can result in two independent sensor observations not being fused
  - Approach: Possible solution is same as inconsistent data, e.g., pdf from distance metric
- Inconsistent Data
  - Problem: ***Transliteration*** of non-English names of people and orgs
  - Approach: develop a distance metric between identifiers and use this metric to condition the probabilities
- Spatiotemporal uncertainties
  - Problem: No common ***frame of reference***
  - Problem: No common ***observation time***
  - Approach: convert to common frames of reference with uncertainties

Soft Sensor Uncertainties
Deception, Veracity, Aging

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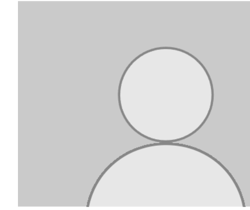
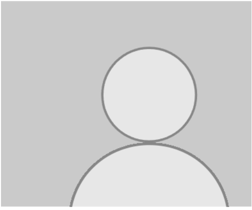


- Deceptive postings
  - Problem: Most effective when it is designed to ***reinforce an existing plausible explanation*** to a series of events
  - Approach: Some methods of detecting deception are known
- Veracity
  - Problem: ***Lack of agreement*** of statement or report ***with fact***
  - Approach: use historical data to assess the veracity of a source
- Aging of data in databases
  - Problem: Some knowables are immutable but others, such as target location data, clothing, and political leanings, ***may change over time***
  - Approach: Automate uncertainty growth and knowledge loss with time linked to type of data

Introduction to Sensor Management, © K. Hintz

Soft Sensor Uncertainties: Bias & Observer Reliability



- Bias
  - Problem: ***Systematic distortion*** of an expected statistical result which may be ***unintentional*** as in human reports
  - Approach: How to detect deception and counterdeception are known
- Reliability of the observer
  - Problem: Degree to which repeated measurements of the same subject under identical conditions yield ***consistent results*** but usually do not have sufficient data for ***accurate estimate***
  - Approach
    - Objective assessment of the historical accuracy of source
    - Self assessment of reliability from the source itself
    - Consistency of report with prior incidents facts
    - Consistency of information with other independent reports

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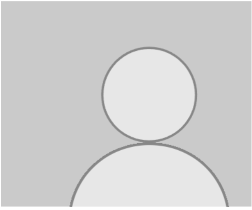

Soft Sensor Information

- Analysis of various types of uncertainties in soft sensors shows pdf's can be conditioned or adjusted to ***quantify uncertainty***
- ***Entropy can be computed*** for soft sensor data
- ***Shannon entropy*** can be used for soft data as well as hard data
- ***Generalized information theory*** (GIT) can be used for soft data
- Information measures can be used to characterize the effects of ***both hard and soft*** sensor observations

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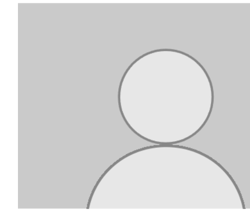
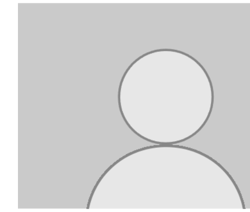


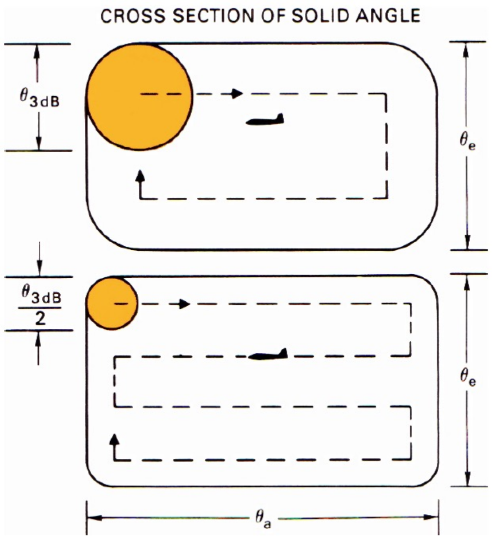
Alternative Search & Detection Strategies

- ***Direct detection***: equal attention to all cells, e.g., deterministic sequential scan, raster scan
- ***Index rule detection***: maintain a probability density function of the surveilled volume and points the sensor at the most likely place for a target to be
- ***Machine learning***
  - Reinforcement learning (RL): goal based, trial and error strategy which determines the next area or volume to search based on a current measurement
  - Virtual associative networks graph-theoretic representation of learned associations, self-partitioned search space

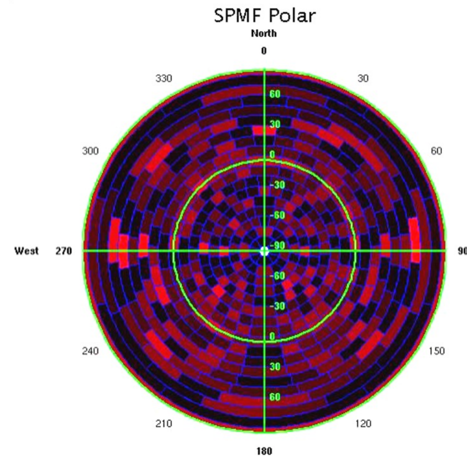


Search & Detection Strategies

G. W. Stimson, Introduction to Airborne Radar, 2nd Ed., Mendham, NJ: Scitech Publishing, Inc., 1998.



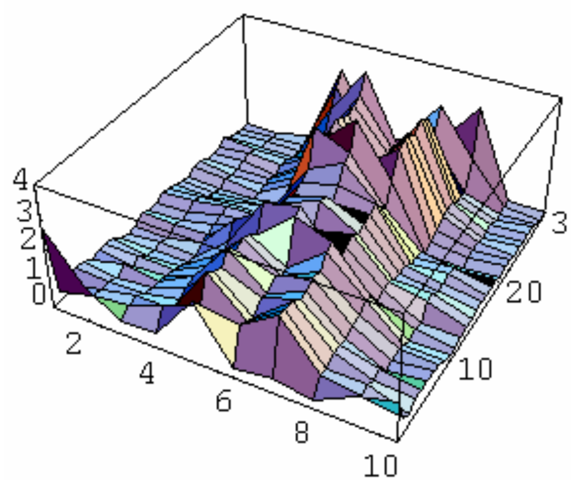
Direct Detection



K. J. Hintz, "Multidimensional sensor data analyzer", US Patents 7,848,904, 7,848,904

Index Rule Detection

Reinforcement Learning



S. H. Musick and R. P. Malhotra, "Sensor Management for Fighter Applications," Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, 2006.

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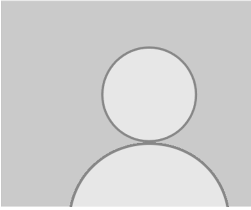
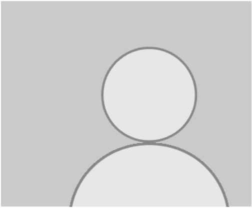
Target Models



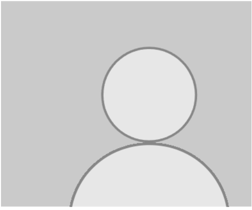
- Particle filters: ***sequential Monte-Carlo***, posterior distribution represented by set of particles
- Model predicated on mathematical ***model of process dynamics***
    - Kalman filter and non-linear variants: optimal (minimum least square error), linear, unbiased state estimator in the presence of additive white Gaussian noise (AWGN)
- Interacting multiple model (IMM): simultaneously uses ***different target models*** with residuals used to select best target model
- Constrained models: track ground based vehicles based on ***terrain constraints***, e.g., roads, hills

Scheduling Constraints

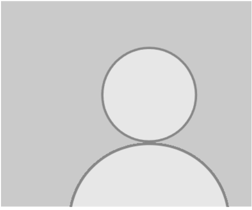


- Temporal constraints
  - ***Timeliness of observation*** to insure no loss of track, e.g., revisit time
    - If track lost, need to waste resources to reacquire
  - ***Reposition time*** for overhead assets
  - ***Timely, accurate*** estimate for fire control solution
  - Sufficient ***dwell time*** for accurate observation
- Radiation constraints
  - Self jamming

Deleterious Interaction of Sensors



- Physical constraints
  - Limited field of regard (e.g., gimbal constraints) means platform may need to maneuver in order to place sensor field of view on target
  - Maneuvering to place one field-of-regard (FOR) limited sensor's instantaneous field of view (IFOV) on a target ***may not allow another sensor on the same platform to maintain its IFOV*** on that or another target
- More of a sensor scheduling problem than a sensor management problem

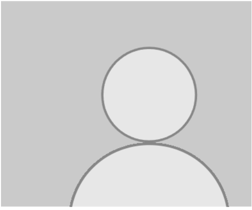


SM Performance Index Goes By Many Names

- Objective function
- Measure of performance (MOP)
- Index of effectiveness (IE)
- Figure of merit (FOM)
- Operational effectiveness (OE)
- Value
- Utility
- Cost
- Cost/benefit
- Measure of effectiveness (MOE)

Introduction to Sensor Management, © K. Hintz

Performance Index



- Many measures are ***heuristics*** related to mission effectiveness rather than direct measures of sensor system performance
- A common objective function is in the form of a weighted sum of a weighted arithmetic mean (WAM)

$$WAM = \sum w_i d_i$$

where d_i is a desirability measure

where w_i is a weight assigned to that measure

Introduction to Sensor Management, © K. Hintz

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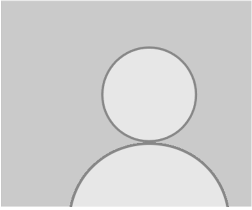
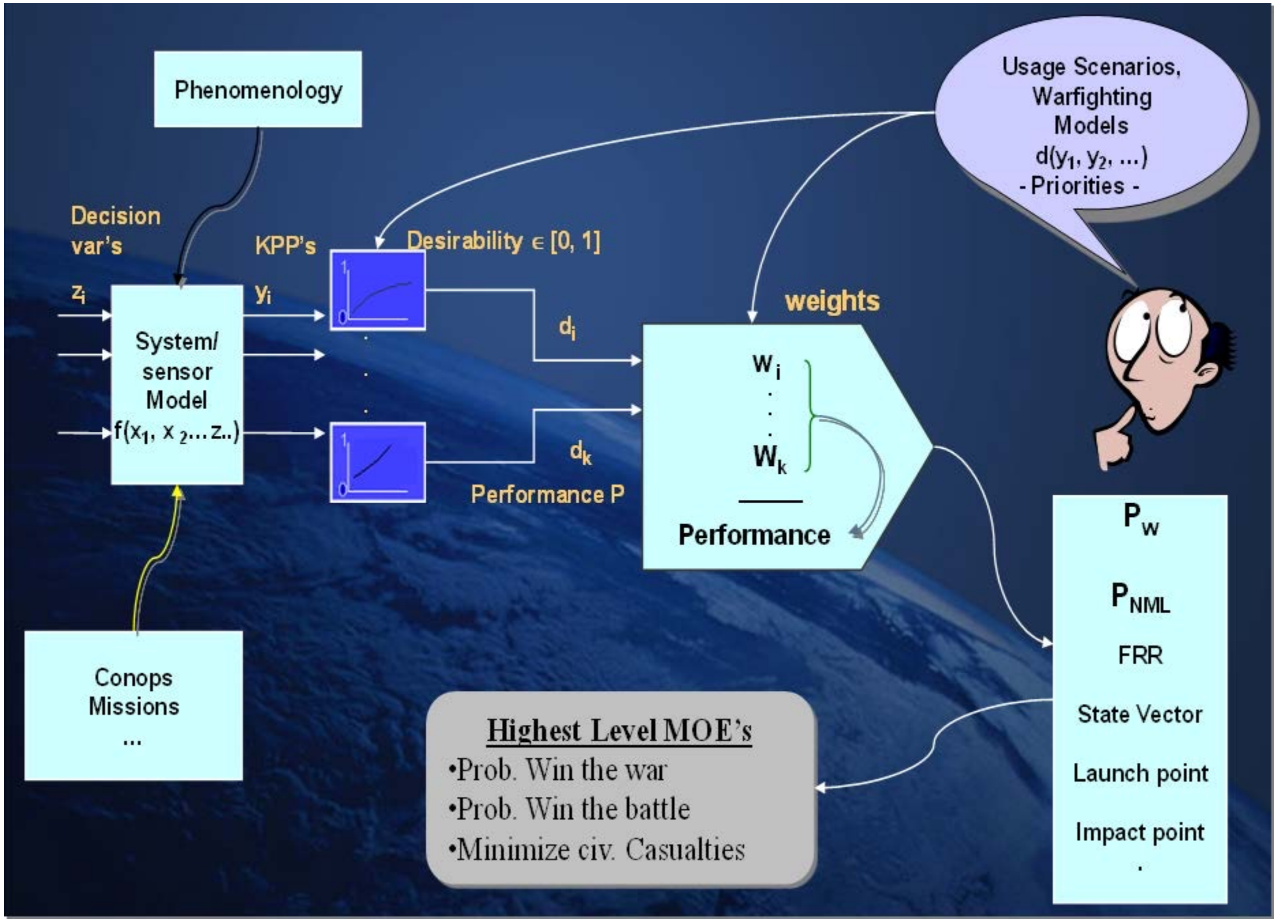


Problems with *WAM*

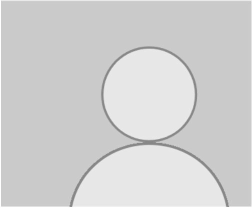
- *WAM* is ***not dimensionally commensurate*** and doesn't make sense
  - What is the weighted sum of probability of detection, probability of not dropping track, minimum tracking error, mission value of target, etc.?
  - Multiple subject matter experts (SME) will not agree on weighting even if they agree on the metrics themselves
- One solution is to normalize the metrics such that they do not have units, but SME problem remains

Development of non-dimensional *WAM* *



* [Rockower, 30]

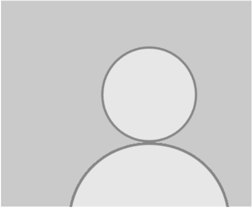
Other Measures of Performance



- Decision theory (DT) and how the outcome of the measurement ***affects making other resource allocations***
- ***Minimizing error*** covariance of a target(s) in track
- ***Threat level*** of adversarial target
- Use of the acquired information relative to ***weapon management***
- Market based approaches with each sensor having a ***budget***

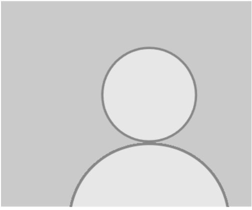
Introduction to Sensor Management, © K. Hintz

Most Important Component of a MOP



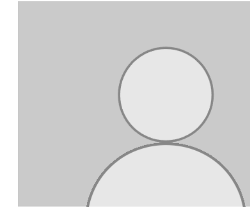
- Purpose of a sensor system is to acquire information (decrease in uncertainty) about an adversary so a ***measure of information must be central*** to SM performance index
- Covered later in tutorial as part of information based sensor management (IBSM)

Theoretical Approaches to SM

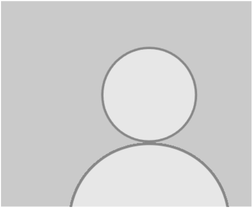


- Global, myopic
- Real-time
- Naïve & point solutions
- Normative or descriptive
- Architectures
- Networked IOT
- Game theory
- Market theory

SM Computation, Global or Myopic?



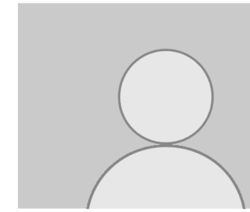
- The ***globally optimal*** (infinite time horizon) sensor management solution is ***not computationally feasible in real time*** and is a difficult combinatorial optimization problem
- A dynamic environment is only ***short-term stationary*** and computational effort is wasted on accounting for the possibilities of future actions which may have a low probability of occurring
- Dynamic programming has been used to effect in ***farsighted sensor*** management applied to a system for move/stop tracking
- It has been shown that the optimal sensor management policy can be found by ***linear programming***, but it is ***computationally intractable*** in real time.



SM Computation, Global or Myopic?

- WRT sensor management, myopic has ***at least two meanings*** with feasible, real-time solutions
  - "A myopic strategy is one where the sensor manager considers only the benefits resulting from a ***single sensor action***." [Nedich *et al*., 19]
  - IBSM: Determine which is the ***best next collection opportunity (BNCO)*** without regard to subsequent actions independent of the sensor which will make the measurement
- Limitation is that there may be a more optimal solution if future sensor actions are included

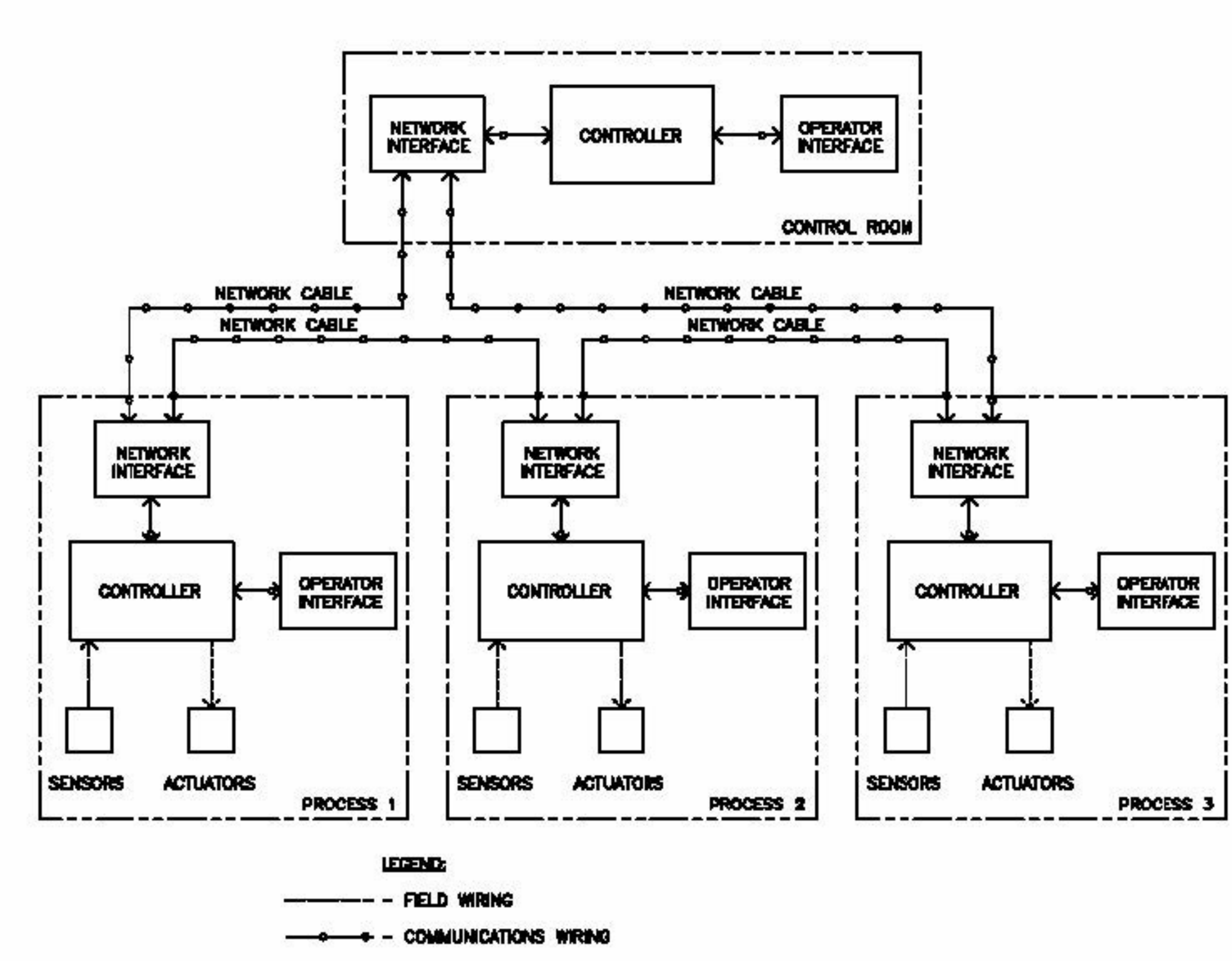
SM Computation, Global or Myopic?



"…Williams *et al.* established in [Williams *et al.*, 20] that greedy sequential methods for measurement planning are guaranteed to perform ***within a factor of 1/2 of the optimal multistage*** selection method. Furthermore, this bound is independent of the length of the planning horizon and is sharp." [Hero & Cochran, 21]

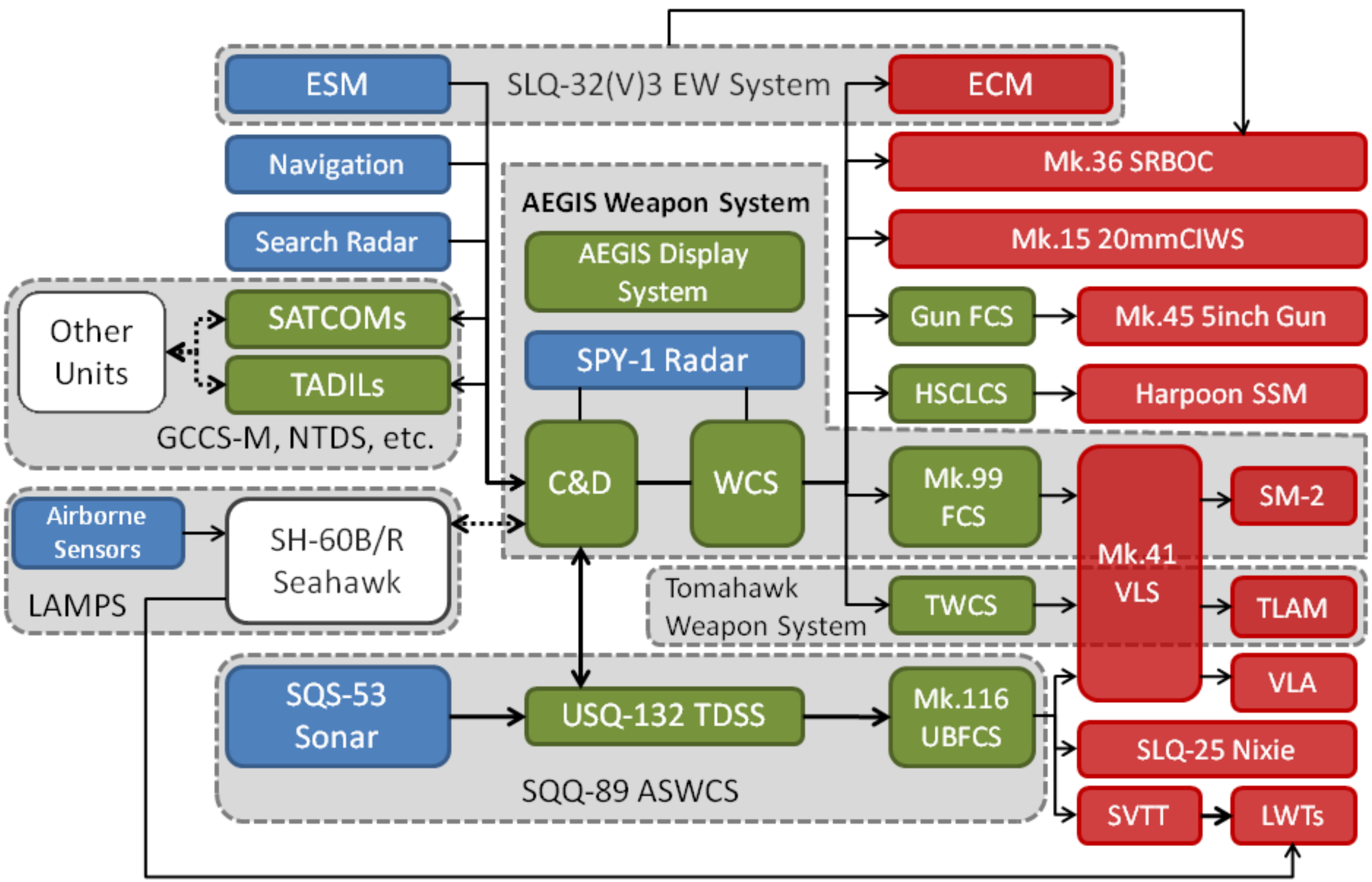
- ***Myopic is satisficing solution***, i.e., good enough for most applications

Sensor ***Scheduler*** Example, SCADA*



* [TM 5-601, 22]

AEGIS Combat System, Sensor *Manager*

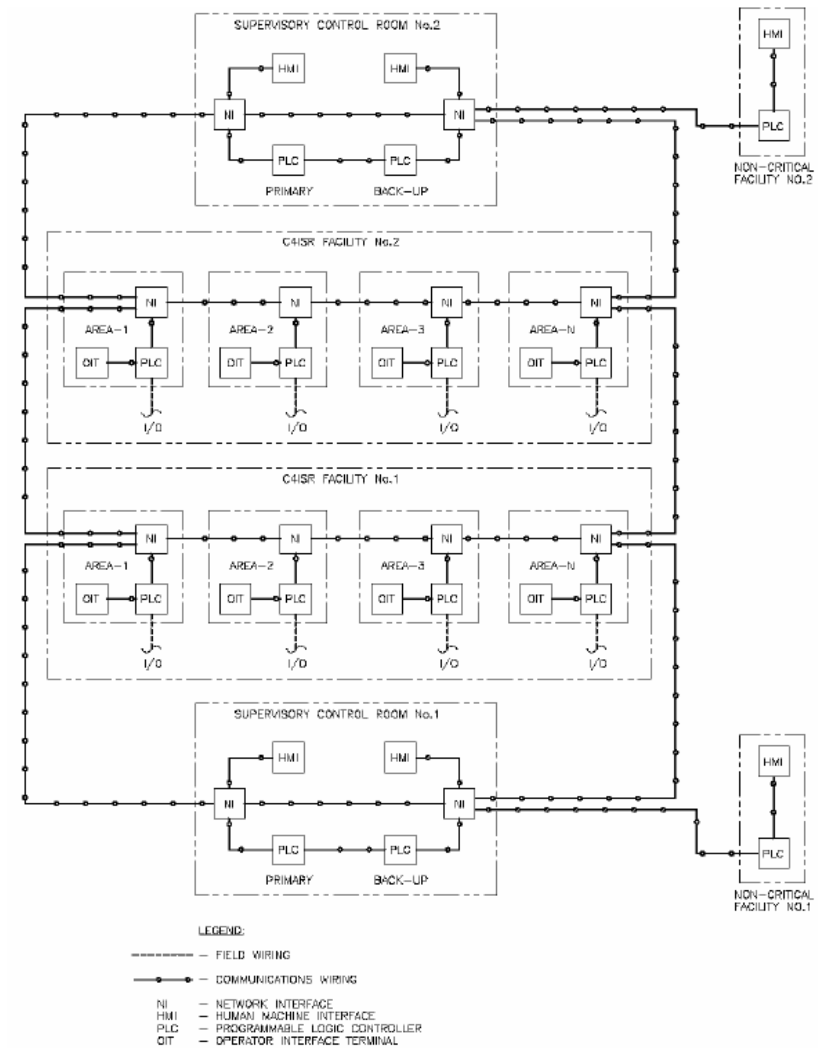


https://upload.wikimedia.org/wikipedia/commons/8/8c/Aegis_Combat_System.png

Simplest SM

Naïve SM: sensors operate ***independently and autonomously*** with their own optimization criteria

- Observations forwarded to centralized location for fusion and information extraction
- Suitable for static environment with deterministic data rates
- Distributed supervisory control rooms

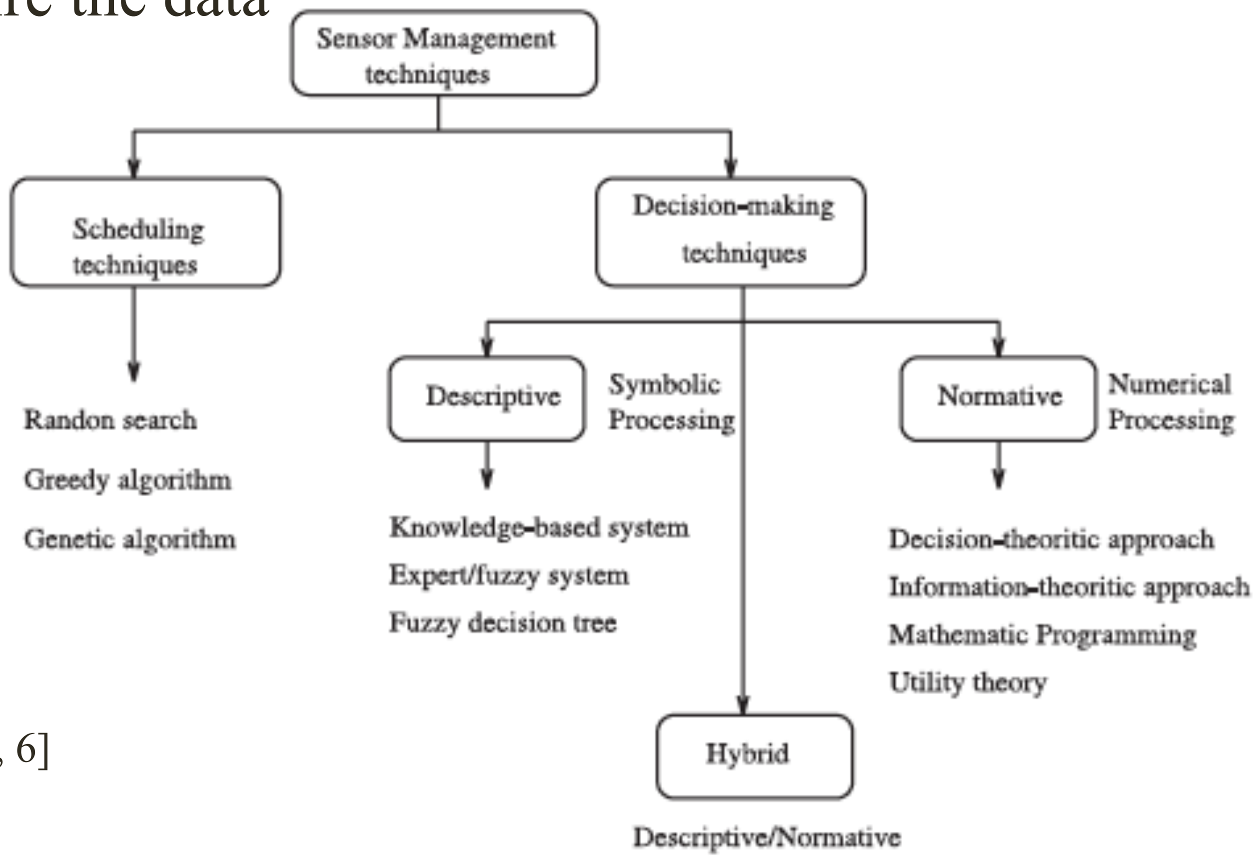


Heuristic Point Solution SM

- Control ***multiple, heterogeneous sensor*** systems
- Designed with a particular optimization criterion in mind and provide good real-time performance for a ***predefined problem***
- Not generalizable
- Not scalable

Decision Making Approaches to SM *

Determine which is the ***most important task*** independent of how to acquire the data



* [Ng & Ng, 6]

Normative Decision Making

Normative: decisions based on relevant numerical data

- Suitable for systems with ***numerical performance index***
- Bayes Net (BN), Markov Decision Process (MDP), Partially Observed Markov Decision process (POMDP)
- Most common normative process based on modeling the state progression of a process as a ***Markov decision process (MDP)***
  - Next state only depends on the most recent state and sensor action
  - Myopic reward function only based on current measurement
  - If not completely observable, then POMDP
  - Solutions possible with linear programming, but not computationally feasible in real time

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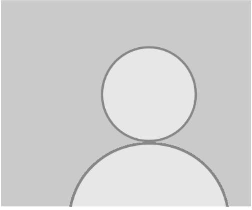
Normative Decision Making

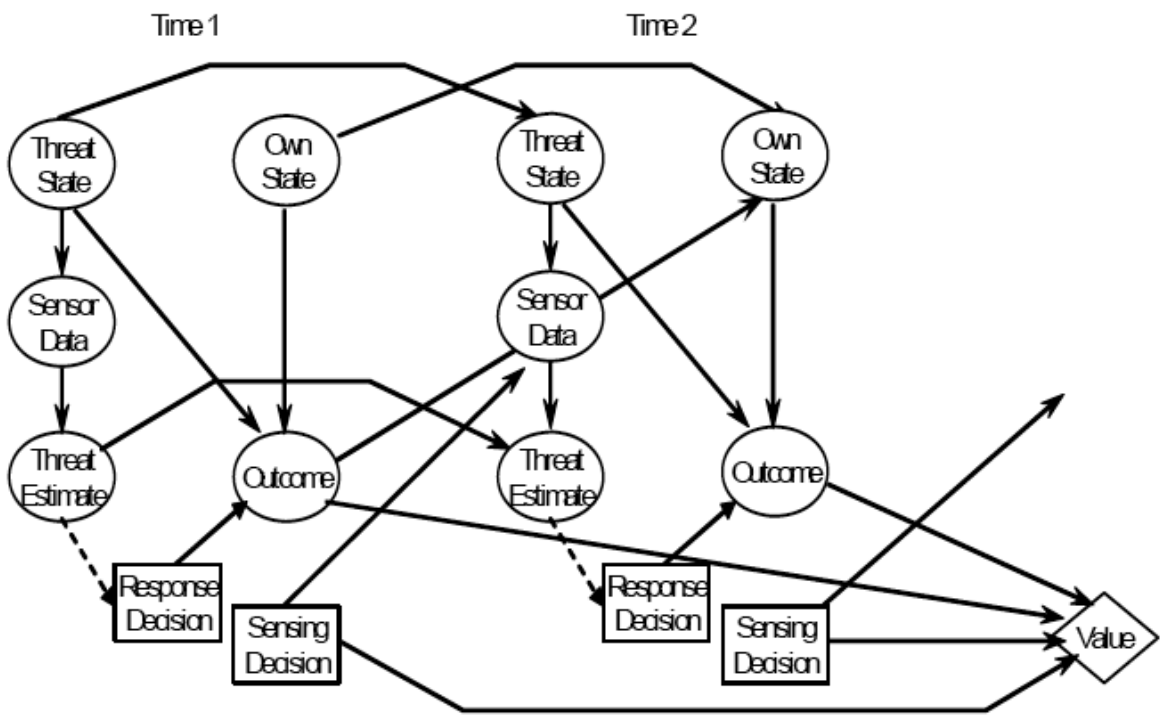


Information based sensor management (IBSM)…covered later in tutorial in more detail

- Two orthogonal myopic performance indices differentiate between ***situation information*** and ***sensor information***
  - Expected (***situation***) information value rate, $EIVR_{sit}$
  - Expected (***sensor***) information value rate, $EIVR_{sen}$
- Bayes Net for numerical computation of ***possible alternative situation*** information gains from which to choose as the best next collection opportunity

Normative Decision Making

Influence diagrams: generalization of BN to include decision making (e.g., a suitable weapon to use against an adversary) problems in addition to probabilistic inference



* [Chong, 31]

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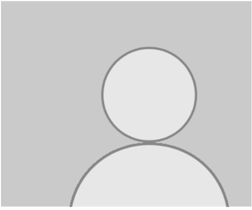
Descriptive Decision Making

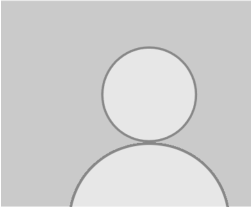


Descriptive: rule based

- Useful if ***no normative approach*** is available
- Attempts to ***emulate human*** decision making
- Knowledge based approaches, Fuzzy reasoning, fuzzy decision trees
- Example rule set [Smith & Rhyne, 23]

R1: IF target is Attacking or Bearing-in or Maneuvering,
THEN the target is Important

R2: IF target is Close and not Friend,
THEN the target is Attacking.



Architecture Based Approaches

- Centralized
  - Most industrial sensor systems have a regular, non-time varying structure amenable to centralized control
  - SCADA
  - Difficulty with centralized control is tendency to micromanage
- Distributed or decentralized
- Hierarchical
- Hybrid of centralized and decentralized

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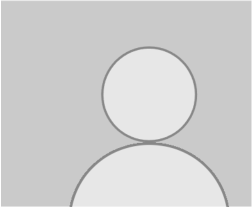
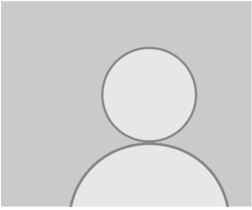
Decentralized or Distributed Control

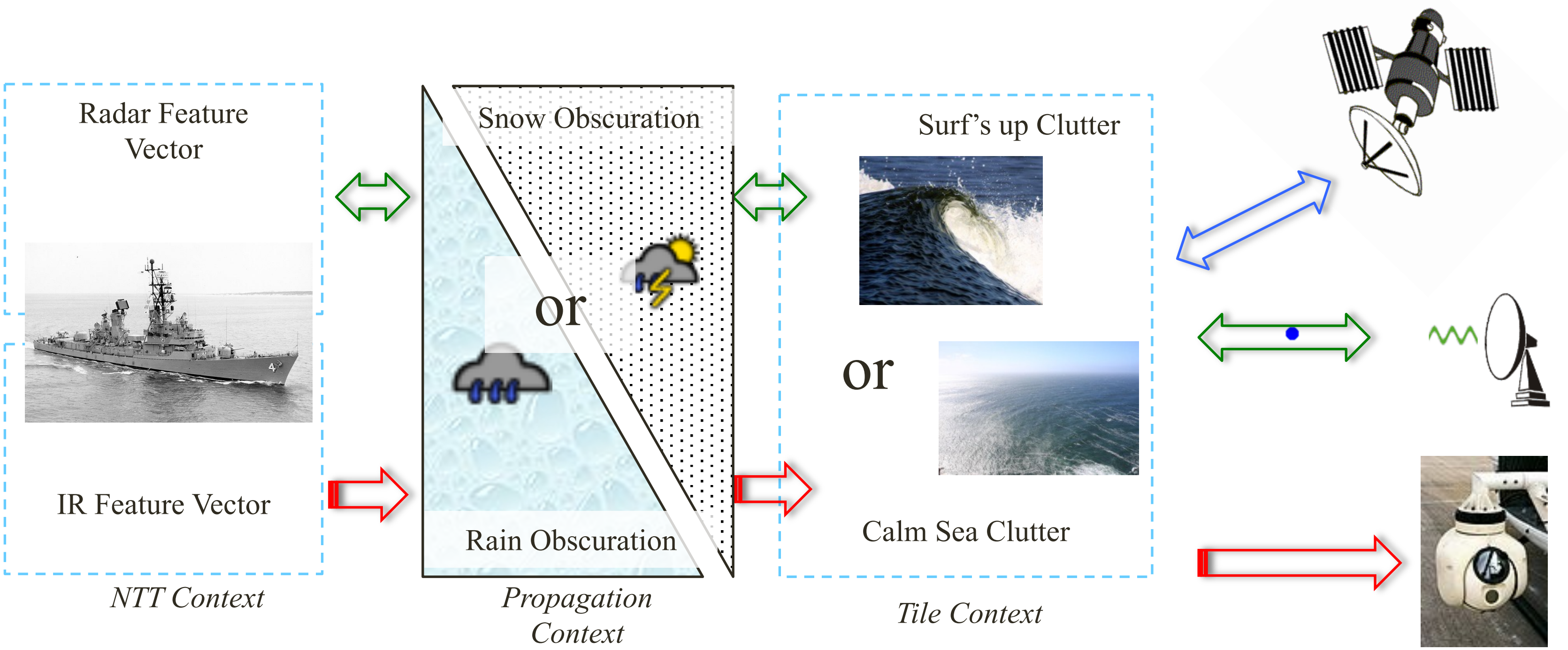


- Counteract centralized micromanagement with ***local intelligence*** to decide best usage of local sensors within tasking
- Decentralized sensor platforms given more generalized information request
- ***Requires more processing power*** on distributed intelligent platforms
- Requires ***coordination*** among sensor platforms
  - Game theory, market theory, hierarchical IBSM

Hybrid Approach

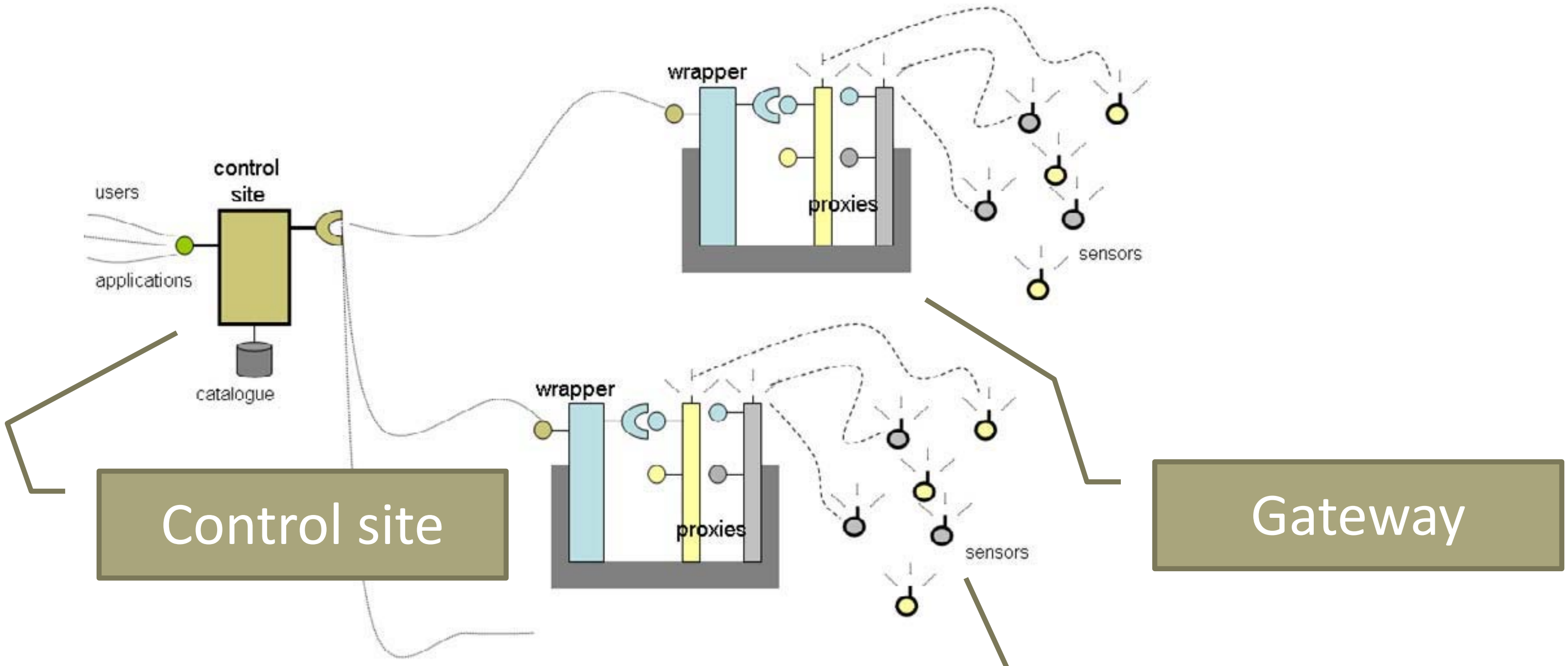


- Best solution does not fit exactly into any one category
- Hybrid of local intelligent control of the sensors which can adapt to the local environment and avoid the trap of micromanagement by a central authority while being self-similar and scalable.



Hybrid Approach

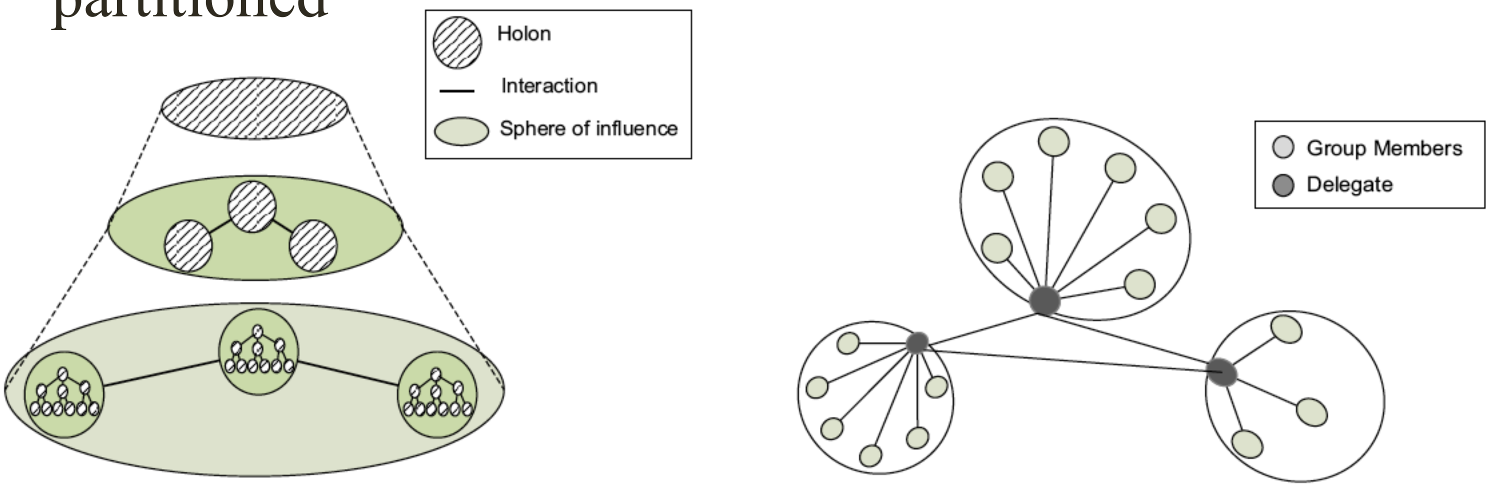
Another hybrid approach to sensor management is comprised of three main levels, sensors, gateways, and control sites.



L. Gurgen, C. Labbe, V. Olive and C. Roncancio, "A Scalable Architecture for Heterogeneous Sensor Management," in 16th International Workshop on Database and Expert Systems Applications (DEXA'05), Copenhagen, 2005.

Holonic & Federated Architectures

- ***Holonic***: autonomous, self-reliant units, called holons that cooperate to achieve the overall system objectives
- ***Federated***: not strictly hierarchical or holonic, but partitioned



(a) Holonic architecture (b) Federation architecture

* [Hilal *et al*., 32]

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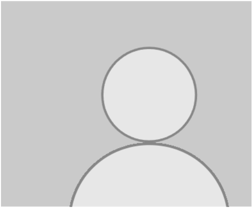
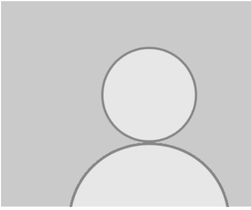
Game Theory

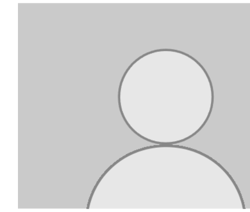


- Game theory can be applied to the tracking of targets, particularly when they are intelligent targets which may change their behavior based on whether they detect that they are being tracked or not
- Assumes ***adversary is playing rational game***
- Partitioned into information based portion and covariance control portion
- Performance measure is sum of ***weighted covariance*** and ***cost***, but same ***noncommensurate*** measure problems
- Even if covariance and info are normalized, no theoretical justification for relative weighting

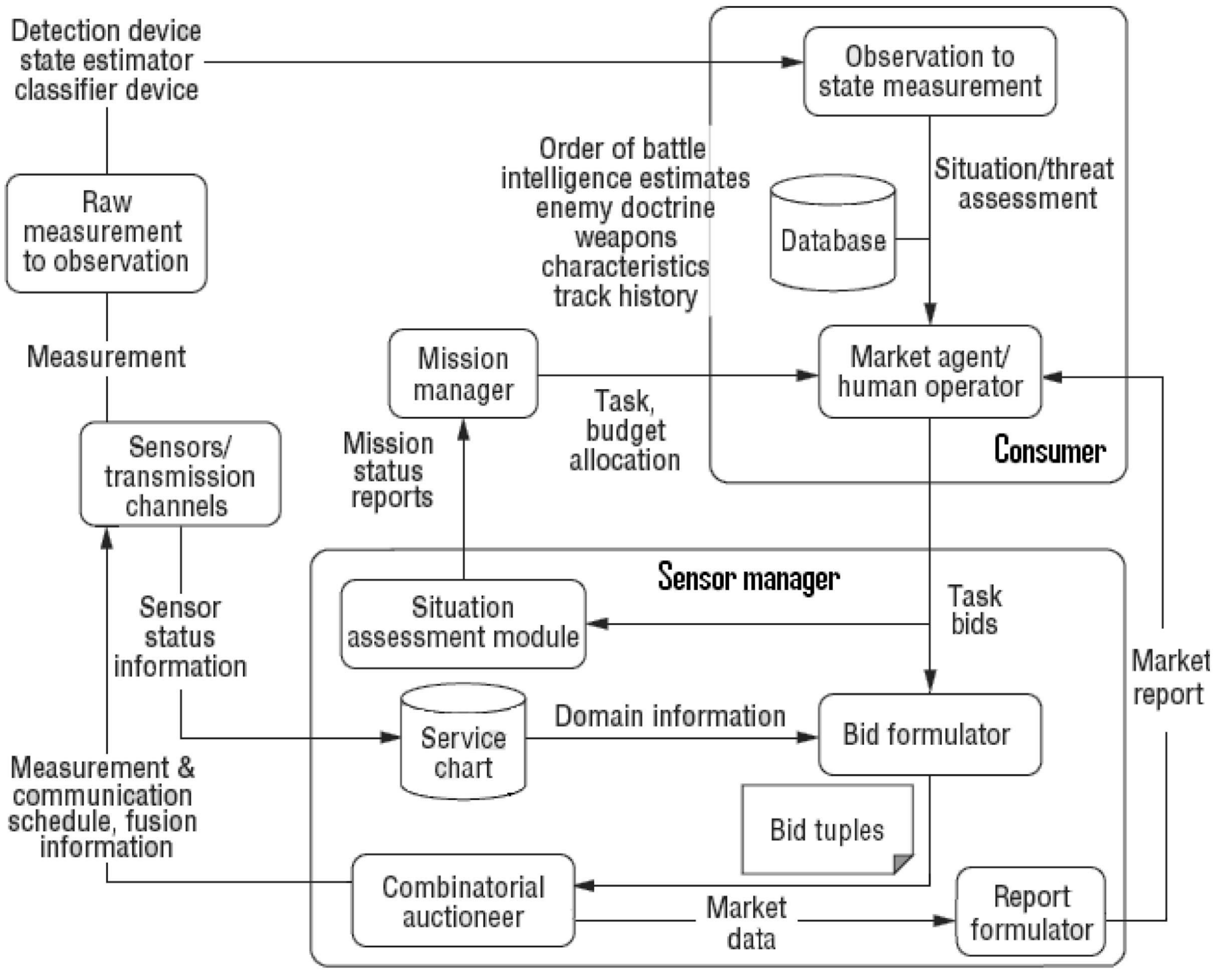
Market Theory



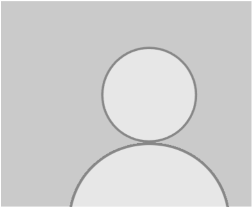
- "The sensor manager (SM) acts as a competitive market for buyers and sellers of sensor resources. Sensors and transmission channels are modeled as sellers. Sensors sell their sensor schedule (i.e., their "attention") and transmission channels sell raw bandwidth. End users, or consumers, of the sensor network are interested in higher-end products such as target tracks, environmental searches, and target identification". [Avasarala *et al.*, 24]
- ***Significant bandwidth cost*** of communications bandwidth consumed to perform negotiations among sensor platforms
- May be suitable for a ***small number of sensors*** on a single platform



Market Theory



* [Avasarala et al., 24]



Market Theory

- Another market based approach assumes that the targets to be tracked are already known and that they can be partitioned into sets of targets.
  - ***Centroid of the sets*** can then be used to determine the cost to the sensor in terms of the time spent observing that cluster
  - Not suitable for large collection of off-board sensors

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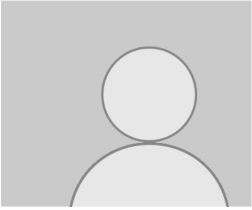
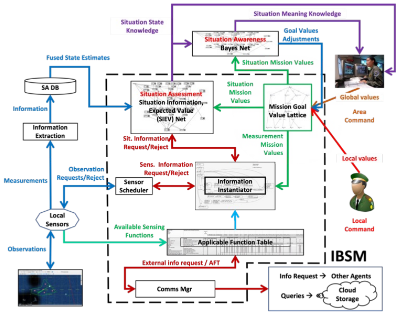


IBSM Approach to SM

- What is the most effective way in which to transfer data from the real world into a model of that world for use by decision makers? *i.e.,* ***obtain valuable, timely, actionable intelligence***
- Commensurate optimization criterion for sensor management
  - Transfer ***information*** not just data
  - ***Mission valued*** information
  - Maximize the ***probability*** of obtaining that information
  - Obtain the information in a ***timely*** manner
- Implementation considerations
  - Computable in ***real-time*** or reasonable planning horizon
  - ***Scalable***, *i.e.,* self-similar structure
  - Reduce communications ***bandwidth***
  - Firm ***theoretical basis*** for design guidance

Short Break



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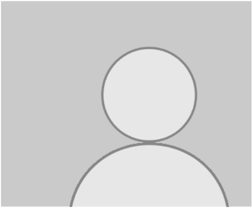

Information Based Sensor Management (IBSM)

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Outline of IBSM Presentation

- Motivation for information based sensor management (IBSM)
- Underlying principle is maximizing expected information value rate, *EIVR,* from the real world to the mathematical model of the world
- Situation information *vs* sensor information
- Functional decomposition of sensor manager into six orthogonal, realizable components
- Network of IBSM managed platforms
- Benefits of IBSM

Motivation for IBSM: Requirement and Constraints

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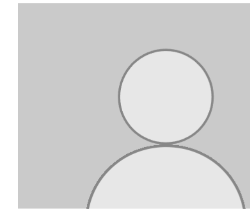
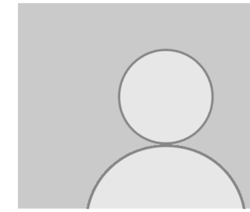
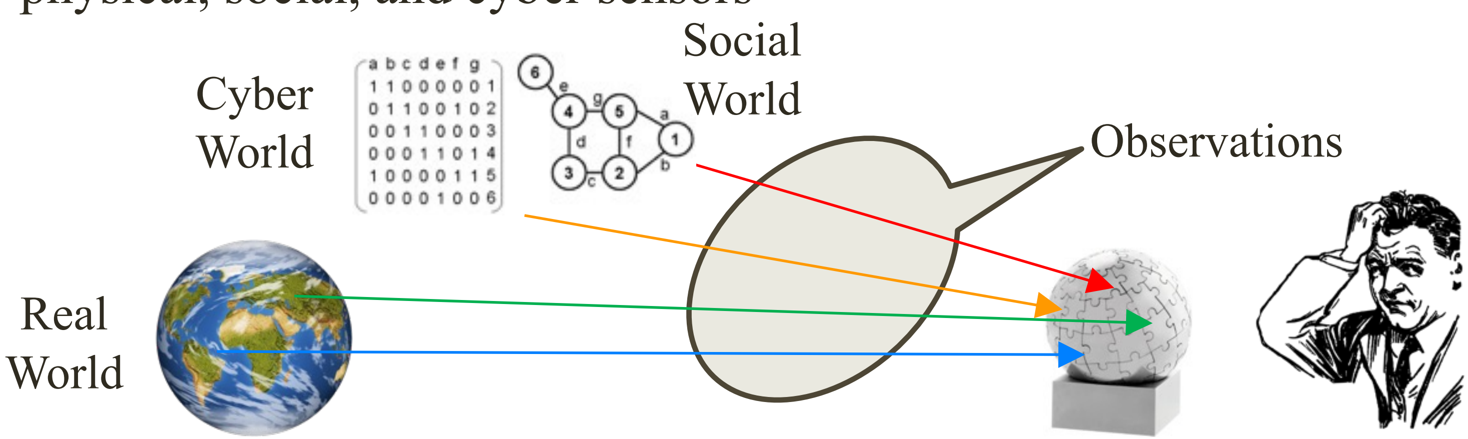


- Integrate sensors with ***non-commensurate data (physical, social, cyber)***
- ***Sensors are constrained*** in measurement, computation, and/or data space
- Different informations have ***different mission values***
- Individual sensors can provide ***different observation functions*** which yield ***different informations***
- ***No single sensor has global understanding*** of the situation nor the value of its observation
- ***Adapt*** to dynamic context, environmental, physical, and operational constraints
- Need to produce a ***minimum uncertainty, mission goal valued, integrated world model*** from which to make operational decisions
- Inherent ***human-on-the-loop*** (HOL)
- ***Data-pull*** rather than data-push
- Computable in ***real-time***

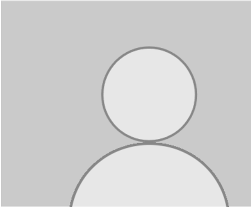
Sensor as a Constrained Communications Channel



- The ***model*** of the world is used by decision makers to make decisions, ***not the real world***.
- From that point of view, one can view the sensor system as a communications channel wherein each sensor is aleady optimized in terms of ***coding the world information into the data it produces***
- We take an egalitarian view of ***sensor***(s) and characterize them as ***any function that observes a process and obtains data***.
- This approach allows for a ***common framework*** for controlling physical, social, and cyber sensors

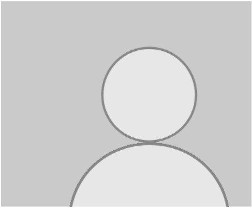


IBSM Views Sensors as Constrained Communications Channels



- ***Shannon*** considered maximizing the flow of information through a communications channel ***without regard to content*** based on signal-to-noise (SNR) and bandwidth by encoding the content
- ***IBSM*** assumes a sensor (communications channel) is performing at its best (in the Shannon sense) and the remaining decision is ***which data to transfer*** from a ***sensor*** in order to improve the ***situation assessment***
- The objective of ***sensor management*** is to maximize the probability of transferring ***mission-valued information*** in a ***timely manner*** from the ***real, cyber, or social*** world into the mathematical model of the world ***for decision makers***

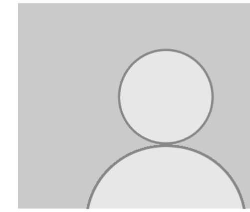
Real-time Computable Commensurate Performance Measure



- The best usage of a sensor is to ***maximize the probability of obtaining the most-valued information in the shortest length of time***, i.e., maximizing the expected information value rate, EIVR
- EIVR is a ***commensurate measure*** which is ***computable in real-time***
- EIVR can be use to evaluate ***situation information needs*** as well as ***sensor information choices***

Introduction to Sensor Management, © K. Hintz

Expected Information Value Rate (EIVR)



- ***Expected*** (probability): Probability of obtaining the information which depends on sensor type, range, SNR, clutter, *etc*.
- ***Information***: The amount of ***sensor information*** and ***situation information*** which can be obtained is ***predictable***, *e.g.*, change in the norm of the error covariance matrix in a Kalman filter state estimator, or a Bayesian network information measure
- ***Value***: The mission value of situation information and sensor information can be computed, *e.g.,* utilizing a mission goal lattice
- ***Rate***: the inverse of the time it will take to obtain the information, *e.g.*, revisit time, dwell time, change orbit time

$$EIVR = \mathbb{E}\left\{\frac{d(IV)}{dt}\right\}$$

EIVR has units of mission-bits/second

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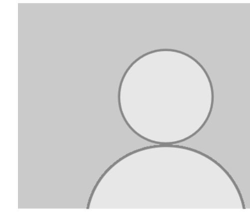
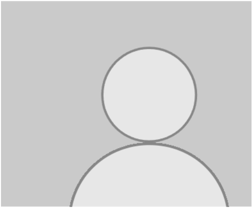


Why Information?

- ***Information***, not data, is the *raison d'etre* for a sensing system
- Need a common reference system within which to evaluate alternative sensing actions
  - Many performance measures for sensor systems are ***noncommensurate***, *e.g.*, P_d , P_{kill} , P_{lost_track} , *etc.*
  - All hard sensing actions can be formulated as entropy changes, hence there is a ***computable information gain that can be associated with each sensor action***
  - Soft observations can utilize ***general information theory*** to measure the ***change in uncertainty which is information***
  - The ***quantity of information can be calculated*** independently of the sensor or source type, its characteristics, or which random variable one is interested in observing

Measures of Information



- Information is measured by a ***change in uncertainty*** about a random variable or hypothesis
- There are multiple forms of information measures including Fisher's, Renyi's, Kullback-Leibler (KL) divergence, Shannon entropy, and generalized information theory (GIT)
- IBSM utilizes a ***change in entropy*** because it is familiar, ubiquitous, and easy to compute

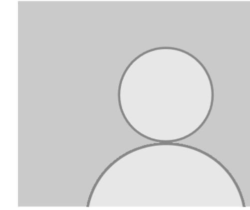
$$H(N_j) = -\sum_{i=1}^{n} P(x_i) log_b P(x_i)$$

resulting in ***information*** being the change in entropy

$$I^+ = H^- - H^+$$

- Entropy changes can be used to compute both ***sensor*** and ***situation*** information

Knowledge Entropy & Temporal Bayesian Information



- ***Knowledge entropy*** (*KEn)* of a Bayesian network at any time is measured in ***bits of uncertainty***
- *KEn* can ***change over time*** due to the leakage of ***kinetic information*** (*KI*) or the acquisition of *KI* through observations
- The *KEn* can be computed as the sum of the entropies of all epistemic nodes in the BN. Formally, the knowledge entropy of a BN, *KEn,* is

$$KEn(t) = \sum_{\substack{all\ epistemic \\ nodes}} H\,(t)$$

- Amount of ***temporal Bayesian information*** (*TBI)* which results from a change in nodal probabilities or network structure from time t_0 to t_1, is

$$TBI(t_1) = KEn(t_0) - KEn(t_1)$$

- With no measurements, there is a ***net loss of information***

IBSM Provides Accurate, Timely, Valued Information For Decision Makers

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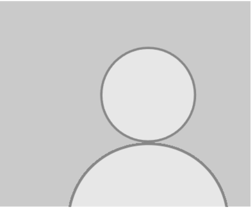
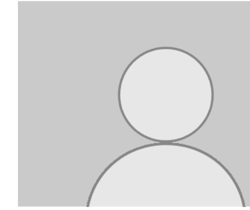


- ***Expected information is computable*** before a measurement
- Not just information, but ***accurate, timely, valued information is needed***
  - Some information is more valuable than other based on current mission goal values
  - Some information takes longer to obtain
  - Some information has a higher probability of being obtained
- Two types of ***non-Shannon information***
  - ***Situation*** information
  - ***Sensor*** (measurement) information
- Best valued uncertainty in world model is achieved by ***maximizing the expected information value rate*** (EIVR) of each sensor observation

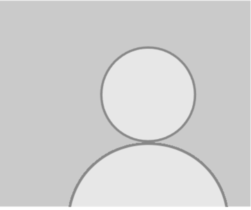
$$best\left(\text{valued world uncertainty}\right) = max\left[\sum_{\text{all targets}} E\left\{\frac{d\left(IV\right)}{dt}\right\}\right]$$

Sensor Information



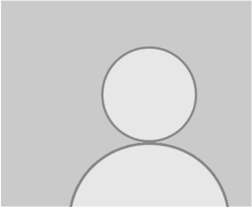
- ***Sensor information*** is a change in uncertainty of a target parameter which results from the ***measurement of a target observable***
  - ***Physical***, *e.g.*, K-filter kinematic state, existence, identity
    $$I_k = -log[\ \|P_k^-\| - \|P_k^+\|\ ]$$
  - ***Cyber & SCADA****, e.g.,* DDOS, intrusion, nation-state
  - ***Social***, *e.g.*, group membership, size, relationship
- Computing sensor information enables the choice of the ***best sensor function*** to satisfy an information request
- Sensor information does not infer a target's motivation or intention, *i.e.,* it measures ***what is, not why it is***
  - Sensor information is ***indifferent*** about why it is needed
  - Sensor information does not do situation awareness but ***enables acquiring the best data for situation assessment***

Situation Information



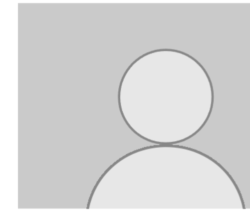
- ***Situation information*** is a change in uncertainty of a ***situation random variable*** (e.g., the *KEn* of a Bayesian Network) which derives from acquired sensor data ***fused*** with context data, *e.g.*,
  - Malware has been detected in our computer system increasing the probability that our computing resources have been compromised
  - An inbound aircraft has been identified as being hostile increasing the probability that we are going to be attacked
  - The population of a local food market has been observed to be lower than the context would suggest indicating the probability of a terrorist attack is increased
- Situation information enables the selection of the ***best next information request*** which will minimize our uncertainty about the situation ***based on our context without regard to how*** to get that sensor information

Implementation of IBSM is Based On Requirements and Constraints



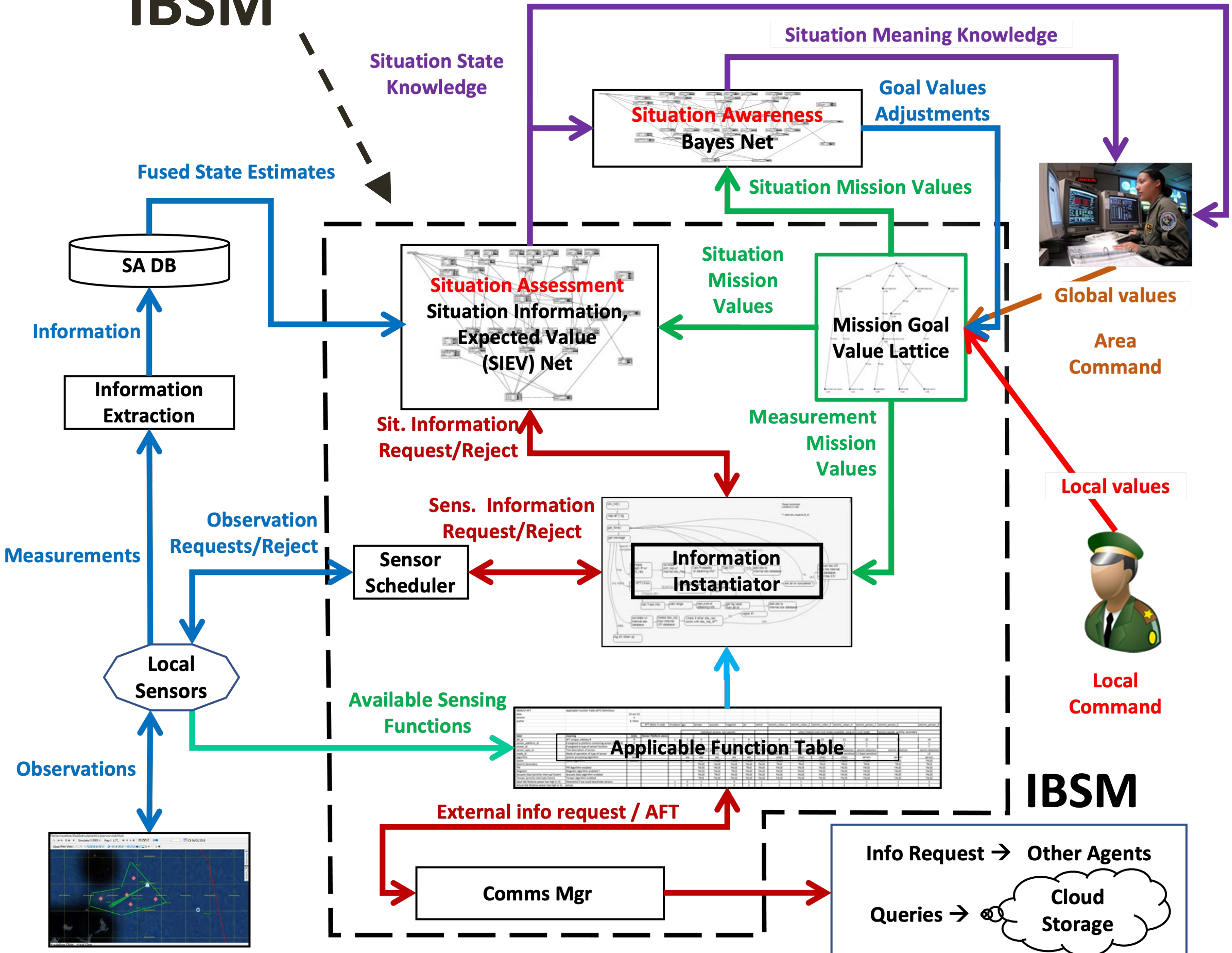
- IBSM is decomposed into ***six essential, orthogonal, necessary, and sufficient components***
- Competing mission goals are computable and valued in a ***mission goal lattice***
- A probabilistic world model has been implemented in a ***Bayesian*** network
- Sensor and situation ***information measures*** have been developed based on changes in entropy

Six Component Parts to IBSM

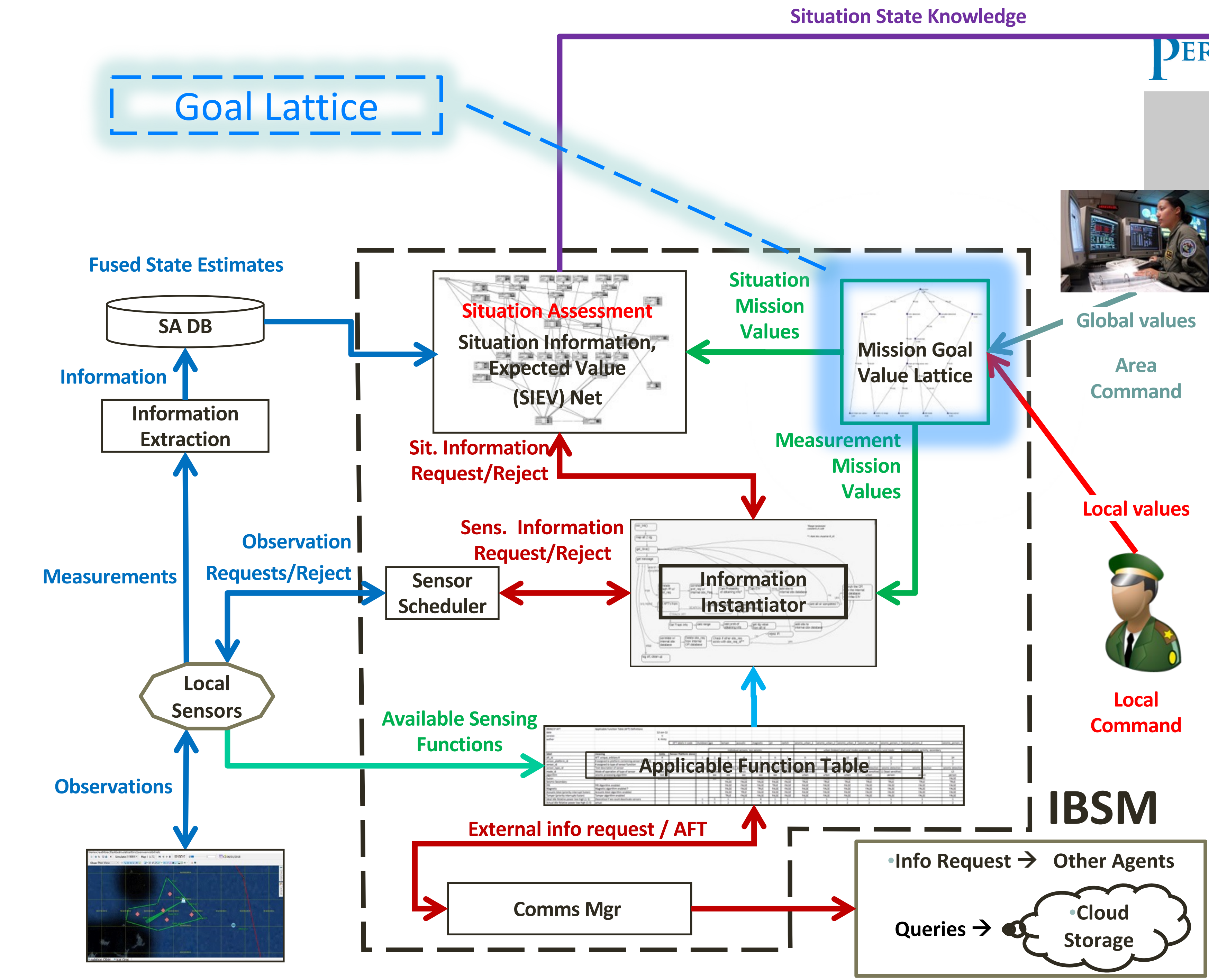


1. ***Goal lattice (GL)*** assigns mission values to situation information needs and sensor observations
2. ***Situation Information Expected Value Network (SIEV-net)*** maintains situation assessment in Bayes Net
3. ***Information Instantiator (II)*** maps situation information needs to sensor functions
4. ***Applicable Function Table (AFT)*** lists available sensor functions
5. ***Sensor Scheduler (OGUPSA)*** distributes sensor functions among sensors
6. ***Communications Manager (CM)*** transmits and receives non-local information requests

IBSM

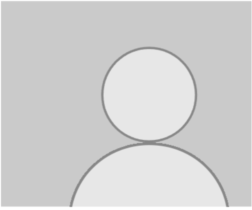


Situation State Knowledge
Situation Meaning Knowledge
Situation Awareness
Bayes Net
Goal Values Adjustments
Fused State Estimates
Situation Mission Values
SA DB
Situation Assessment
Situation Information, Expected Value (SIEV) Net
Situation Mission Values
Mission Goal Value Lattice
Global values
Information
Area Command
Information Extraction
Sit. Information Request/Reject
Measurement Mission Values
Local values
Sens. Information Request/Reject
Observation Requests/Reject
Measurements
Sensor Scheduler
Information Instantiator
Local Sensors
Local Command
Available Sensing Functions
Applicable Function Table
Observations
IBSM
External info request / AFT
Info Request → Other Agents
Comms Mgr
Queries →
Cloud Storage



Situation State Knowledge
Goal Lattice
Fused State Estimates
SA DB
Information
Information Extraction
Measurements
Observation Requests/Reject
Local Sensors
Observations
Situation Assessment
Situation Information, Expected Value (SIEV) Net
Situation Mission Values
Mission Goal Value Lattice
Global values
Area Command
Measurement Mission Values
Local values
Local Command
Sit. Information Request/Reject
Sens. Information Request/Reject
Sensor Scheduler
Information Instantiator
Available Sensing Functions
Applicable Function Table
IBSM
External info request / AFT
Comms Mgr
•Info Request → Other Agents
Queries →
•Cloud Storage

IBSM Component:
Goal lattice with Adjoined Mission Values



- A goal lattice (GL) is comprised of a partially ordered set (POSET) and an ordering relation, e.g., $(G, \leq)$
  - ***Set*** of strategic and tactical ***mission goals*** for a system
  - An ***ordering relation*** specified on these goals
    - *e.g.*, "(this goal) is necessary to achieve (this other goal)"
- Enforce the POSET to be ***a lattice*** by ensuring each pair of goals has a ***least upper bound*** (lub) and a ***greatest lower bound*** (glb)
- Goals on ***top*** of GL are ***soft, difficult to define mission goals***
- Goals on ***bottom*** of GL are ***real, measurable, mission-valued sensor observations***

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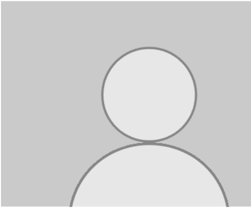
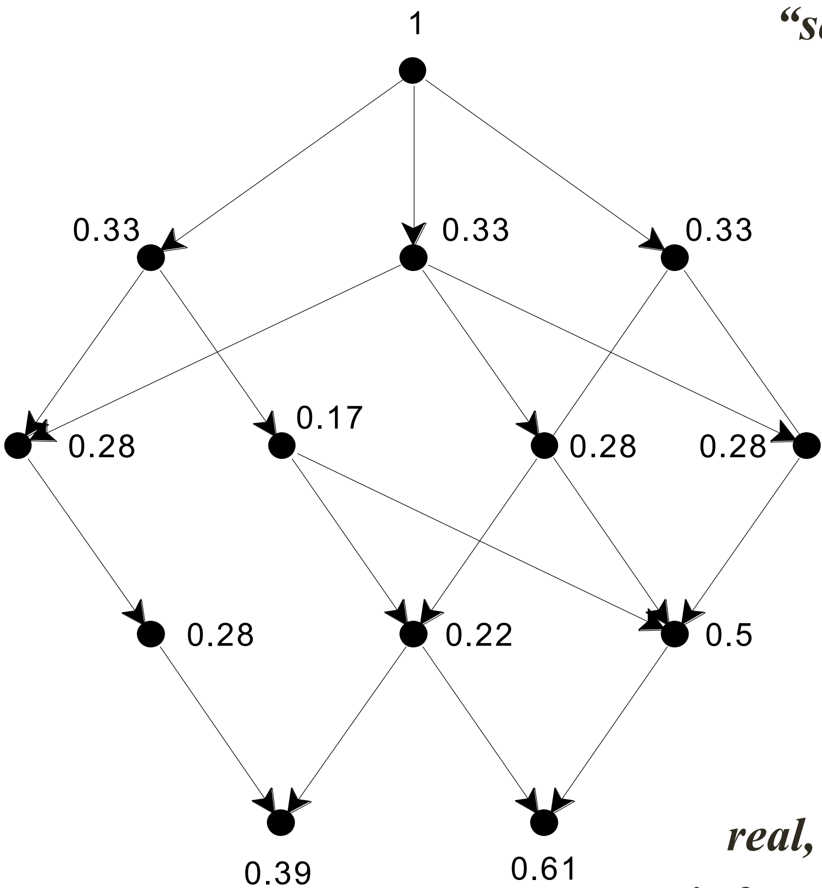
Goal Lattice Apportions Mission Value Among Sensor Actions

- Adjoined to the lattice at each goal is a value
  - Value ***accrues from the (higher) goals*** in which it is included
  - Value is ***apportioned among the (lower)*** goals which it includes
  - The apportionment at each level is ***zero sum***
- Topmost mission goal has value 1
- Lowest goals (real sensor actions) have values based on their contribution to the mission goal(s) determined by the lattice structure and value apportionment

Computing Mission Goal Values in a GL



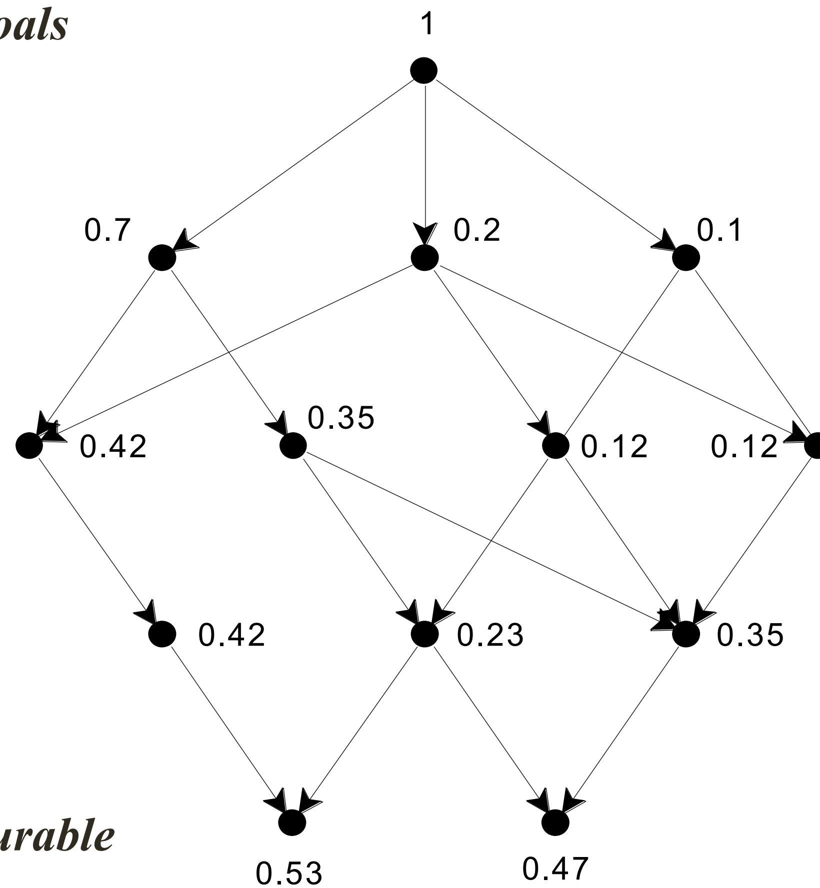
Uniform Apportionment



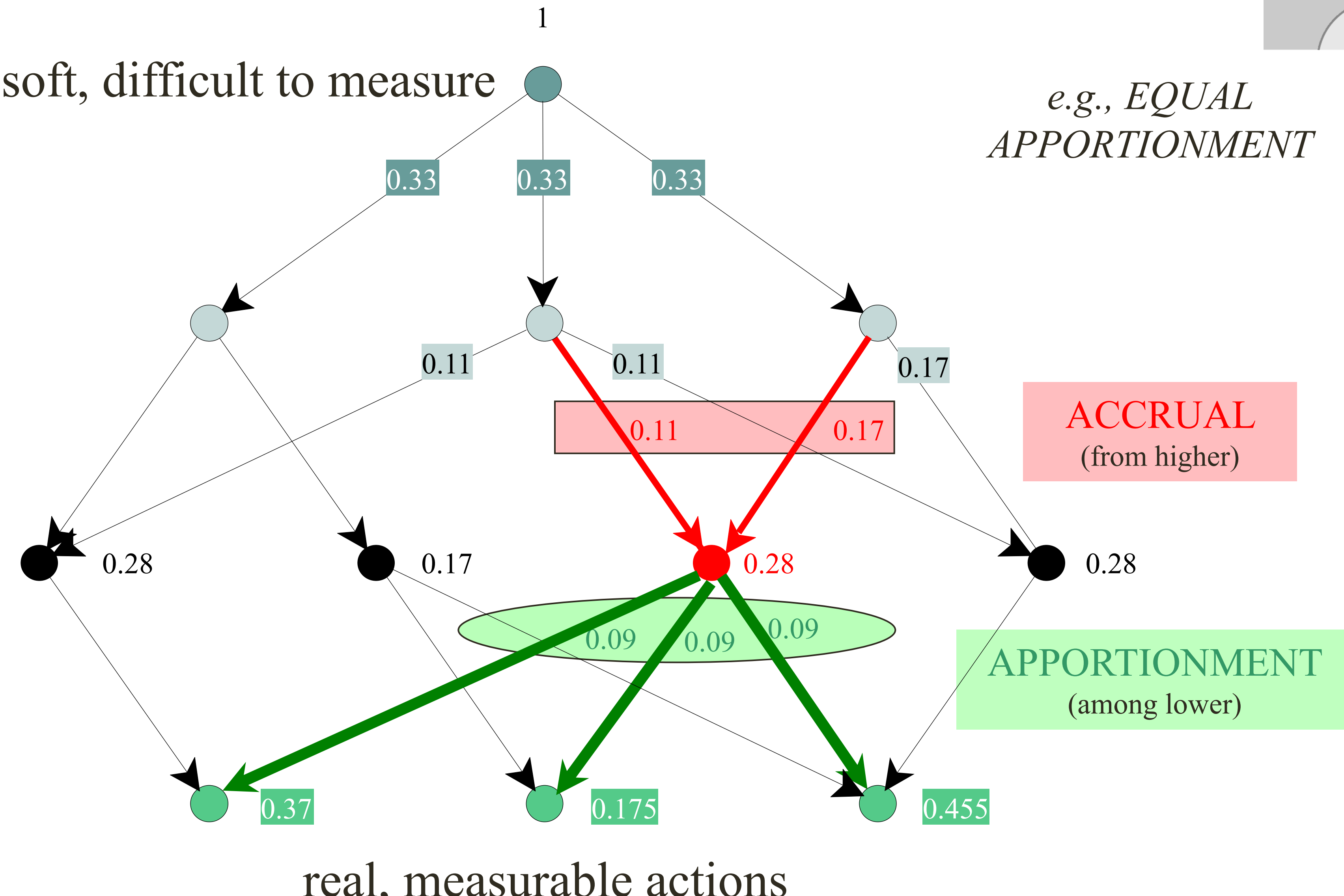
"soft" goals

real, measurable information requests

User Preference



Goal Lattice Numerical Example



Mission-Based GL Example

Topmost goal values used by ***SIEV-Net***

Protect Self

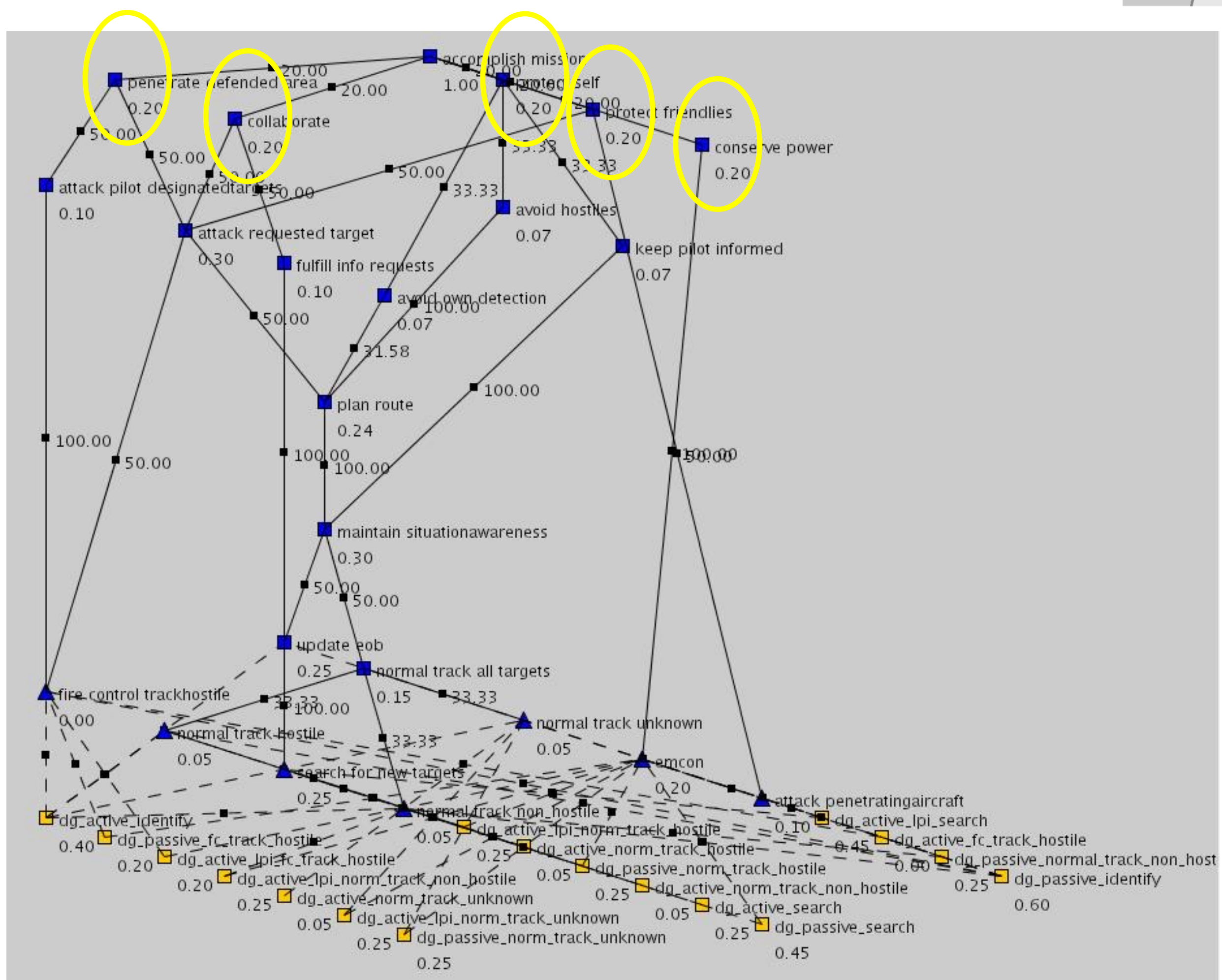
Protect Friendlies

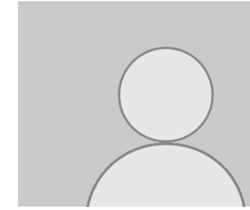
Conserve Power

Penetrate Defended Area

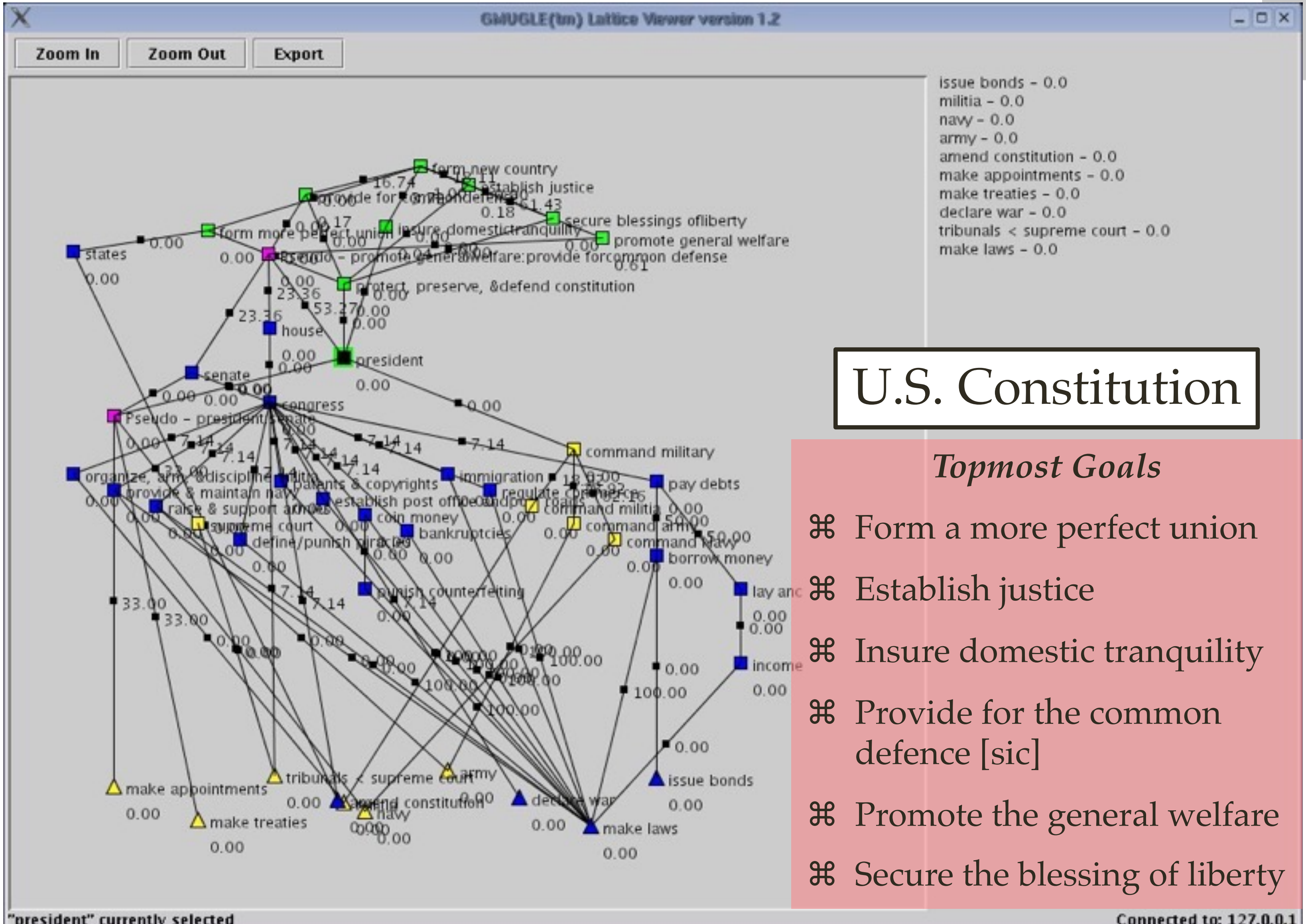
Collaborate

Bottommost goal values used by ***Information Instantiator***





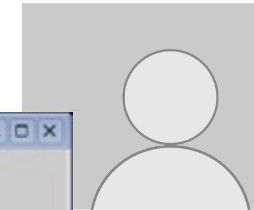
US Constitution Example GL



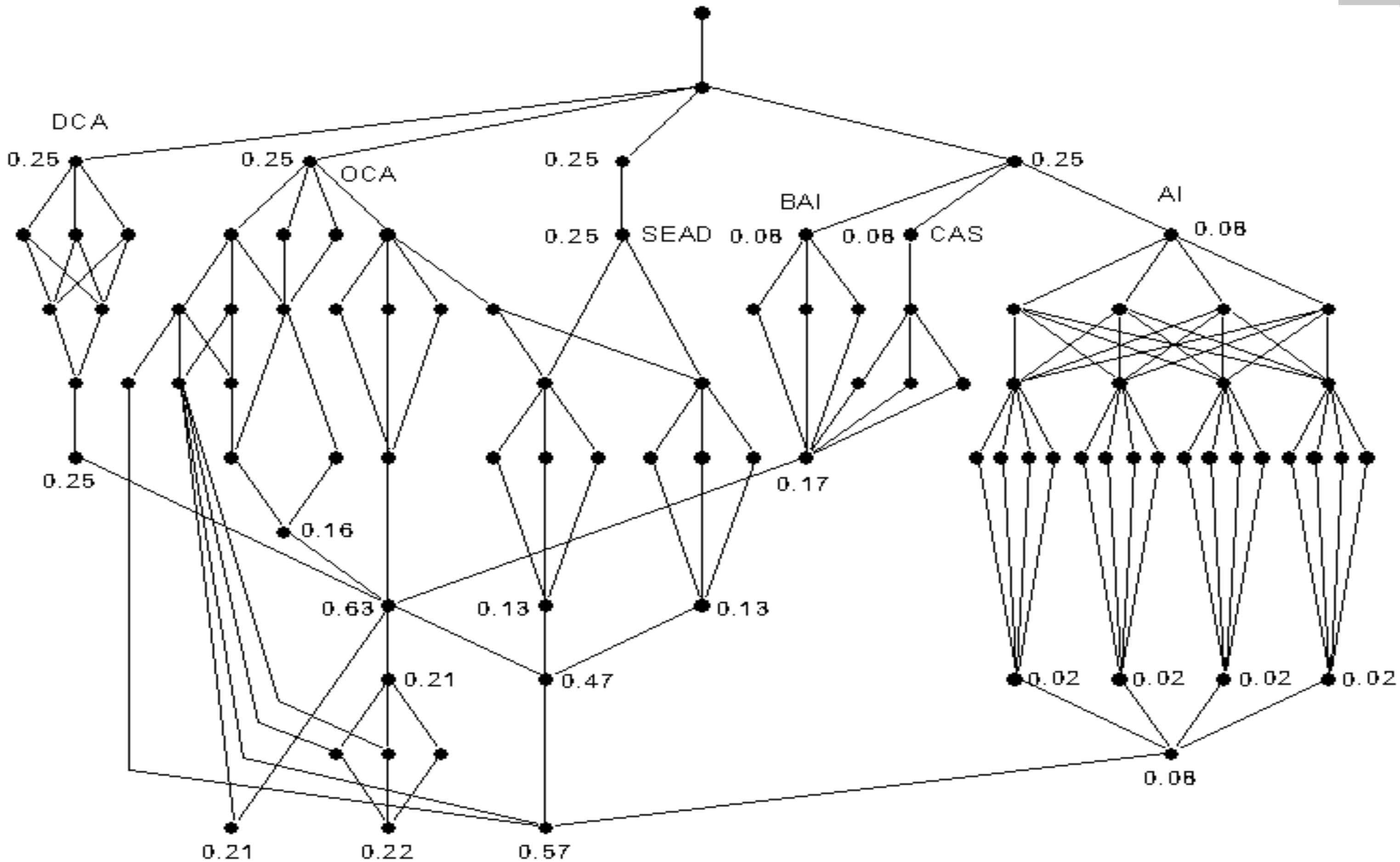
U.S. Constitution

Topmost Goals

- ⌘ Form a more perfect union
- ⌘ Establish justice
- ⌘ Insure domestic tranquility
- ⌘ Provide for the common defence [sic]
- ⌘ Promote the general welfare
- ⌘ Secure the blessing of liberty



Goal Lattice USAF Example



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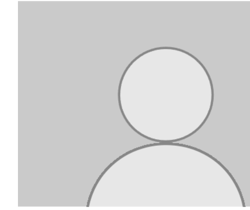
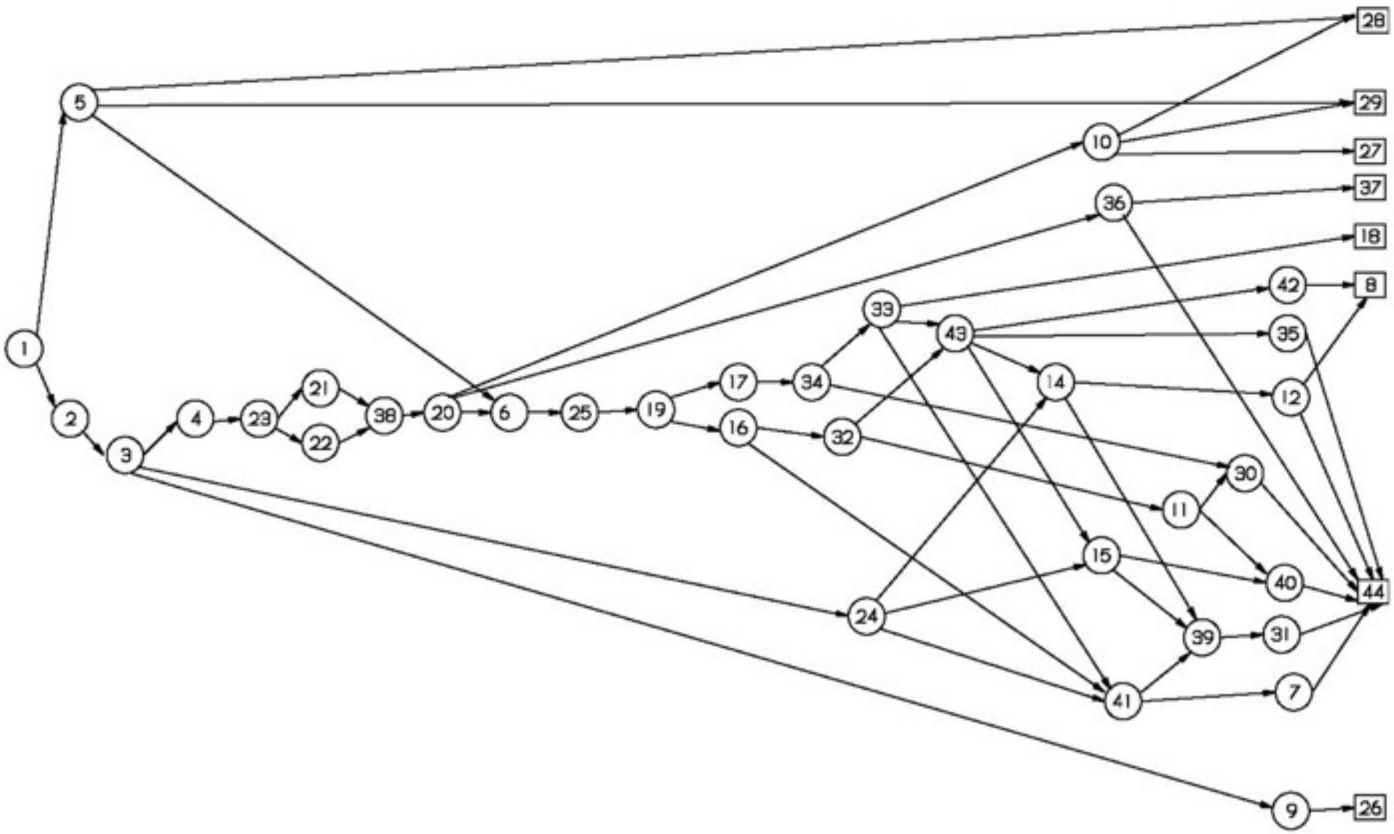
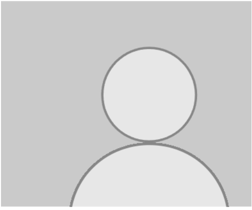


NFL Franchise Goals

1 Successful franchise	2 Keep investors happy	3 Make a profit	4 Sell concessions	5 Keep fans happy
6 Win superbowl	7 Hire special teams coach	8 Provide quality training facilities	9 Profitable TV contract	10 Provide large stadium
11 Develop effective plays	12 Hire good defensive coach	13 --	14 Hire good defensive players	15 Hire good offensive players
16 Score points	17 Deny scoring by other team	18 Keep players happy	19 Win games	20 Maintain a good image
21 Sell full price tickets	22 Sell discount tickets	23 Sell tickets	24 Meet salary cap	25 Win division
26 Attract large TV audience	27 Tax breaks	28 Provide timely transportation	29 Provide security at games	30 Hire good scouts
31 Pay players well	32 Develop good offense	33 Develop good special teams	34 Develop good defense	35 Talented cheerleaders
36 Develop good media relations	37 Have quality commentators	38 Market franchise	39 Effectively trade players	40 Hire good offensive coach
41 Hire good special teams players	42 Keep players healthy	43 Develop team spirit	44 General Manager	45 --

NFL Franchise GL





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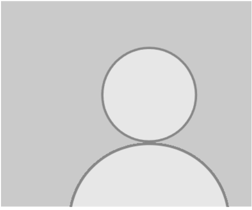
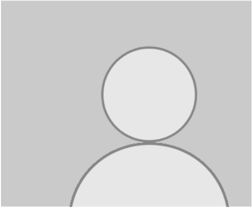
Goal Lattice Creation

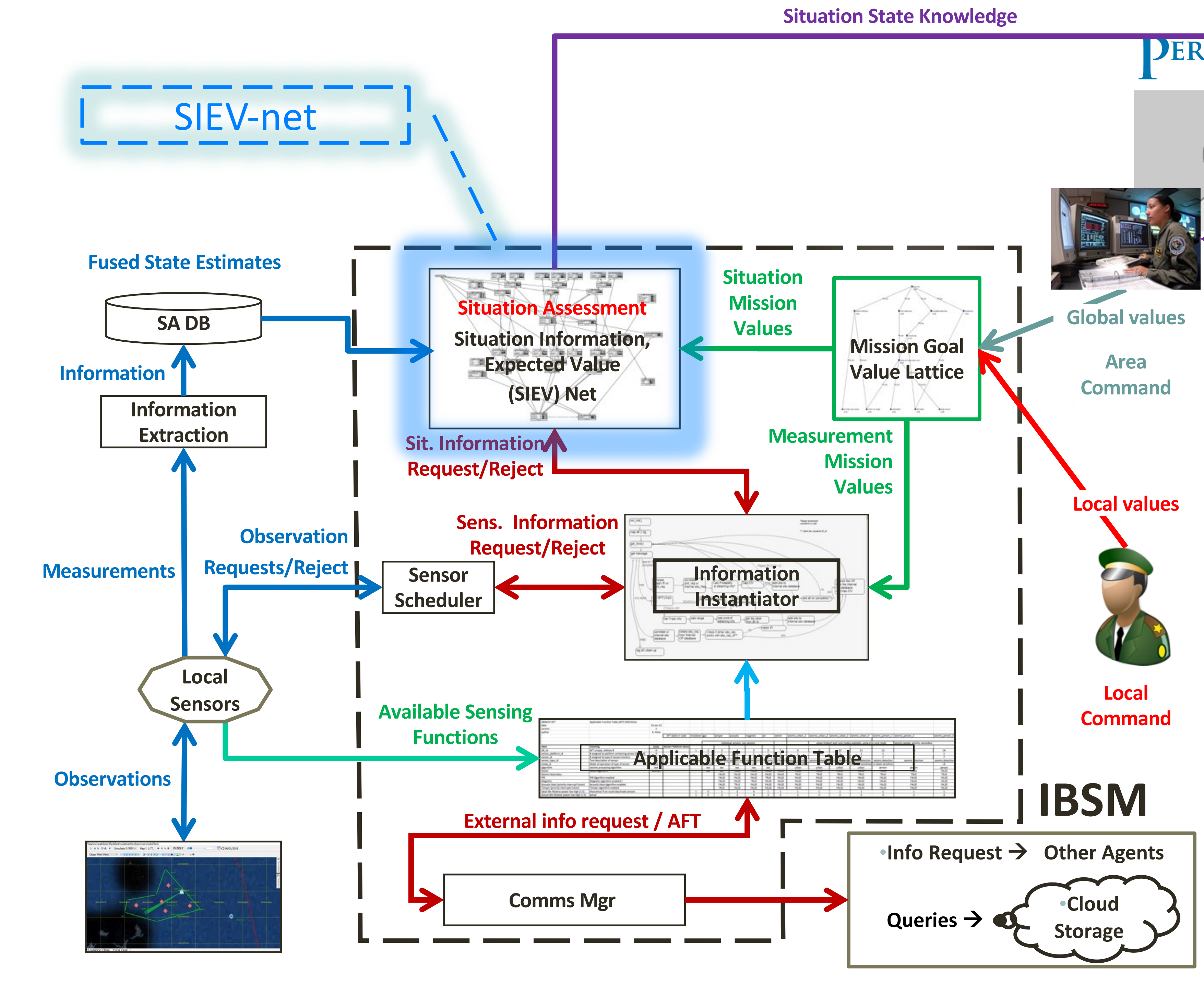


- Web client is used by mission planner to ***create and modify goal lattice structure and values***
  - Enter and edit goals
  - Specify relations among goals
  - Goal Lattice Engine (GLE) is a background process
    - Insures lattice integrity
    - Automatically creates missing goals (pseudo-goals) if required to form a lattice
    - Computes goal values
- ***Dynamic goals are instantiated/uninstantiated in real-time***
    - Diversity of sensors
    - Multiplicity of sensor modes
    - Inclusion of EMCON and power management in static GL
    - Intermittent availability of on-board and off-board sensors
    - Graceful degradation



Benefits of Goal Lattice

- It ***quantifies*** and makes measurable amorphous, ***non-measurable,*** "soft" goals
- It forces the system designer to ***quantify the interrelationship*** among system goals
- GL enables ***implicit collaboration*** of sensing platforms through the use of common shared goals
- ***Shared goals*** are passed from higher level command to lower level sensing platforms
- Use of GL ***enables Human-on-the-Loop*** (HOL) control rather than slower, less effective Human-in-the-Loop (HIL)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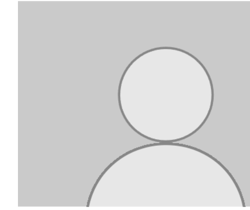
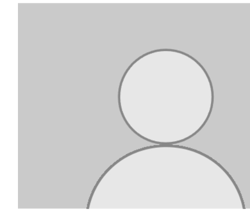
IBSM Component: Situation Information Expected Value Network



- ***Situation assessment*** is crucial to the IBSM paradigm since it allows us to decide ***what information we need*** while ***not (yet) deciding how to obtain that information***
- An extension of ***Bayes net*** can be used for situation assessment
  - ***Information gain*** of a Bayes Net is computable as a potential change in knowledge entropy
  - The effect of obtaining different types of information on global situation assessment ***can be computed a priori***
- A computation on a Bayes net formulation can be ***used to decide what information would maximally reduce our uncertainty*** about a situation and hence, allows us to determine what information to acquire ***without concern for how to obtain that information***

SIEV-net Partition



- SIEV-net is built on a ***causal Bayesian Network***
- Chance nodes are subdivided into
  - ***Non-managed*** nodes
    - Sources of probabilistic data over which ***we have no control***, *e.g.,* air order of battle, electronic order of battle, are we being attacked?, *etc*.
  - ***Situation*** nodes
    - ***Hypotheses about our situation***, *e.g.,* hostile/friendly, target identification, target kinematics, *etc*.
    - Change in probability and/or error covariance is K-L information gain
    - ***Dynamically instantiated*** when target detected and/or characterized
    - Topmost goal value assigned to one or more situation nodes
  - (Sensor Manager) ***Managed*** nodes
    - Probabilities whose values can be affected by launching of information requests

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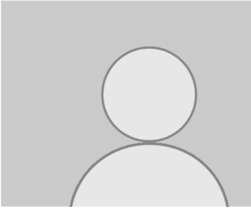

Context is Introduced into IBSM via Unmanaged and Situation Nodes

- SIEV-net is a ***dynamic, object-oriented, causal Bayes Net*** (OOBN)
  - Newly detected targets are instantiated as new situation chance nodes, thereby changing the context through their inter-related conditional probabilities
- SIEV-net is ***contextual***
  - ***Unmanaged evidence nodes provide global context*** info as conditioning probabilities
  - Newly instantiated ***situation chance nodes provide local context***

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Need for Information Measure

- Amount of ***temporal Bayesian information*** (*TBI)* which results from a change in nodal probabilities or network structure from time t_0 to t_1, is

$$TBI(t_1) = KEn(t_0) - KEn(t_1)$$

- The ability to predict the amount of situation information we would obtain ***if we were to take*** a sensing action (update a managed node) allows one to make an ordered list of "best next collection" opportunities based on the maximizing the expected ***situation*** information value rate (***EIVR***$_{sit}$)
- The result of this ***what-if*** is an ordered list of situation information requests that is passed to the information instantiator in order to obtain the highest valued, lowest uncertainty, information

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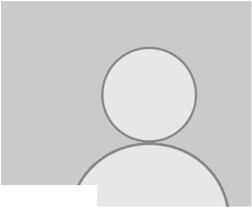
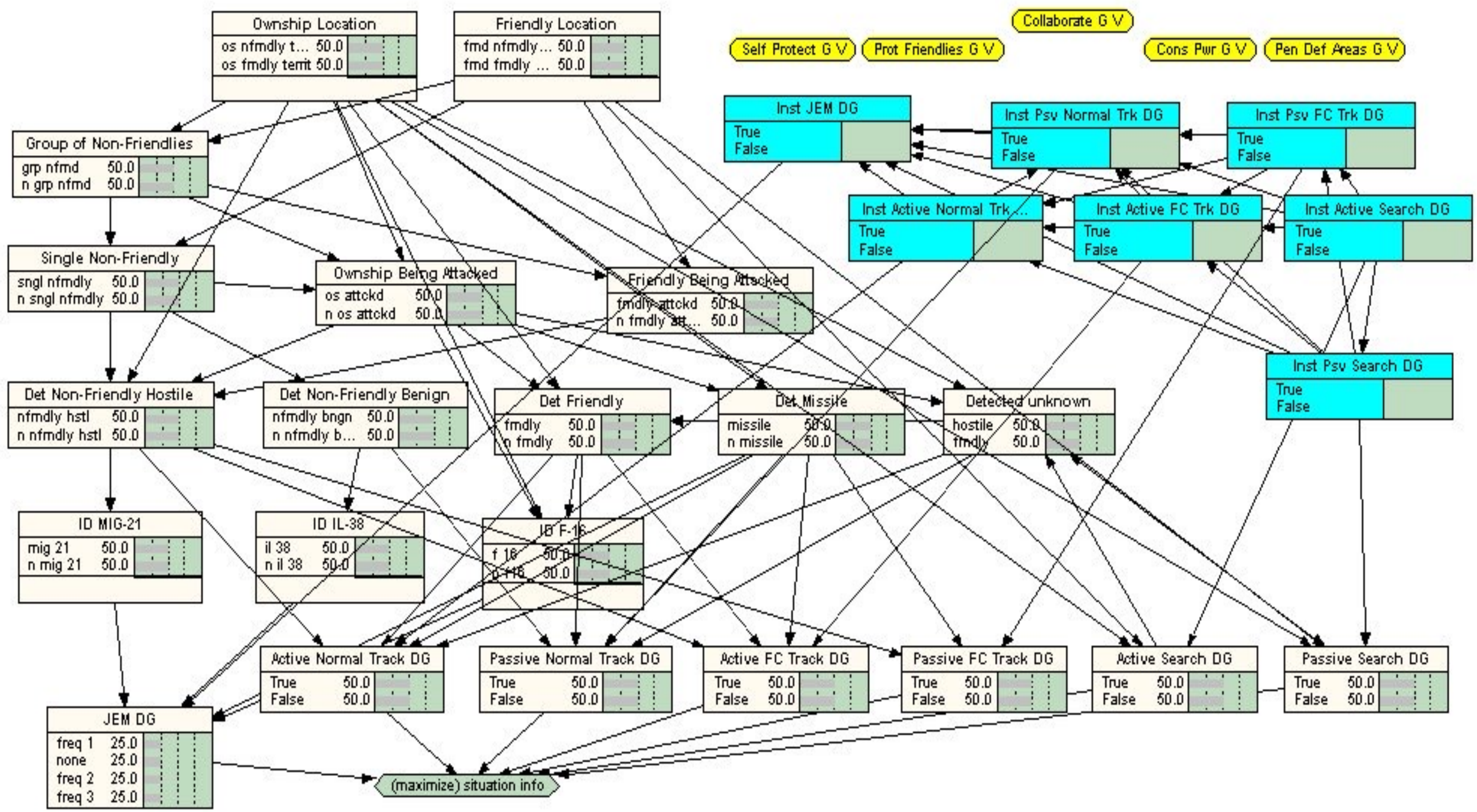
Example SIEV-net





Partitioned SIEV-Net Showing Managed Evidence Nodes (Sensors)

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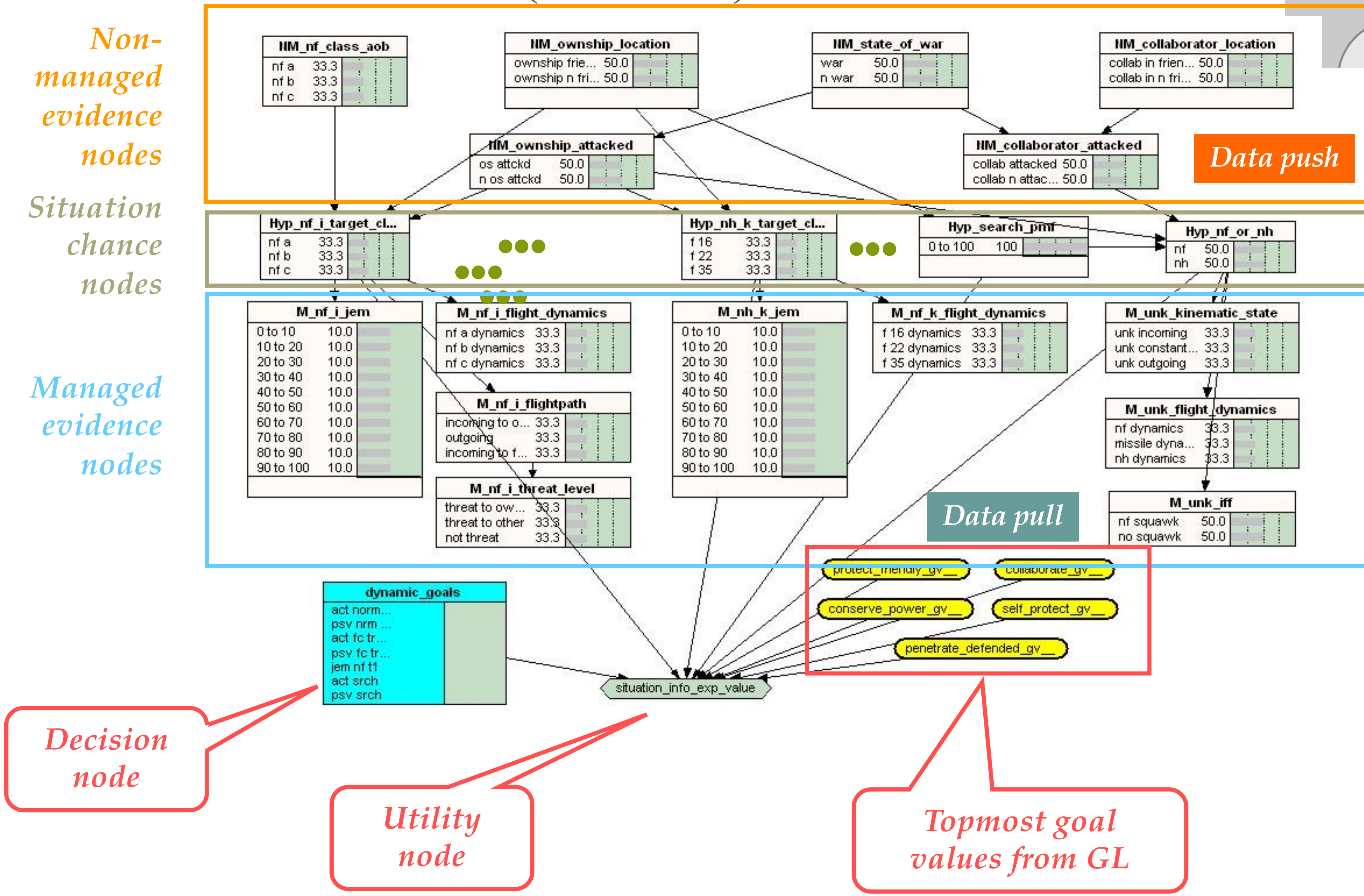
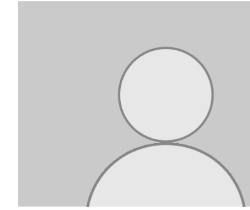
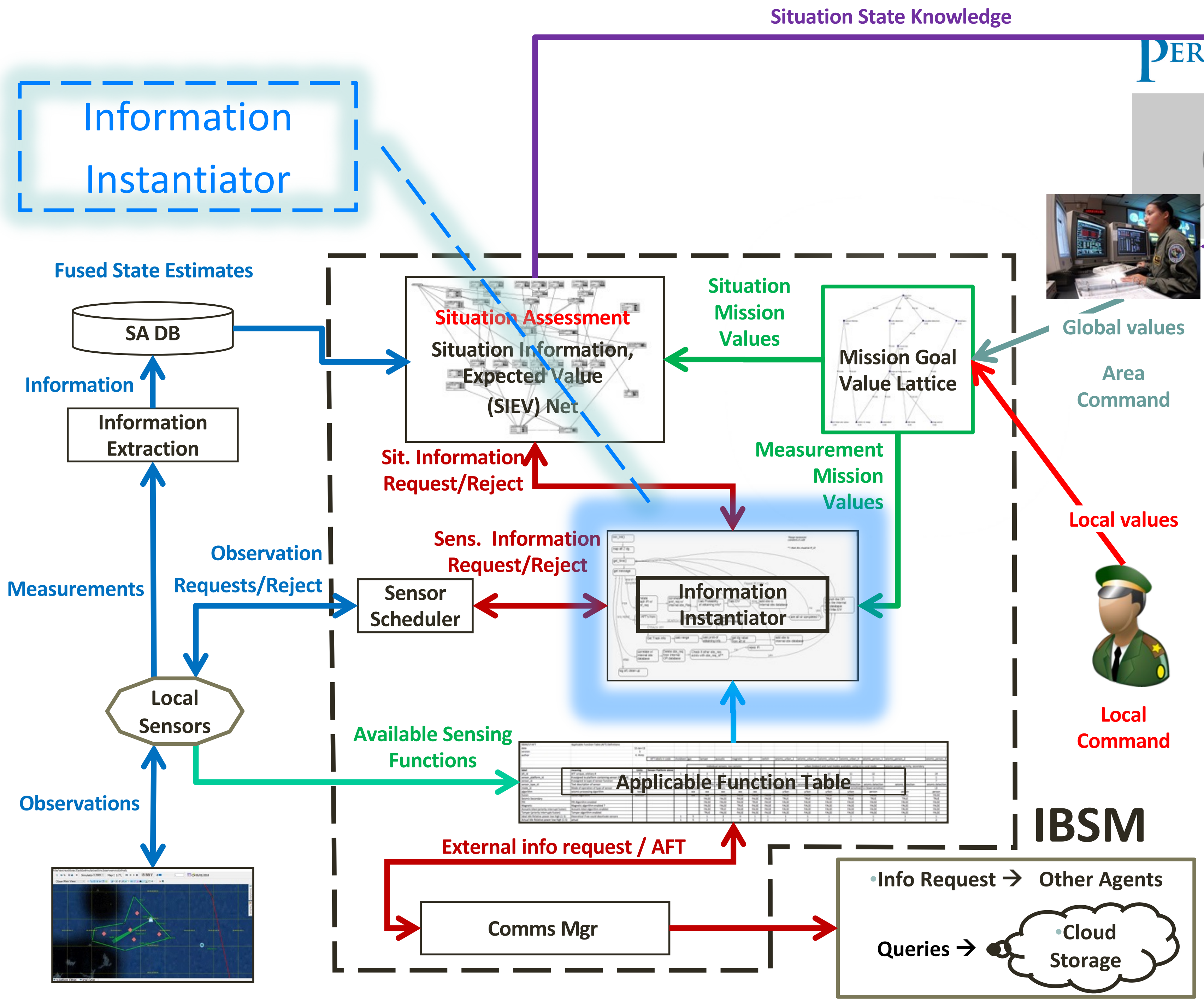


Usage of the SIEV-Net



- $EI_{sit}VR$ is computed for all Bayes Net nodes producing an ***ordered list of best next collection opportunities*** (BNO)
- List is generated ***without regard to how*** that information will be obtained
  - The ***topmost goals*** of the mission GL are associated with situation chance nodes
  - The historical probability and duration of obtaining that situation information is known
- The managed node which will produce the greatest $EI_{sit}VR$ will then be sent to the ***information instantiator*** (II) as a situation information request
- ***SIEV-net does not care how*** the information is to be obtained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IBSM Component: (Situation) Information Instantiator

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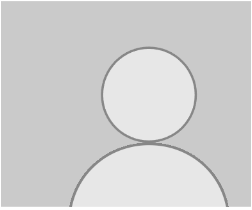
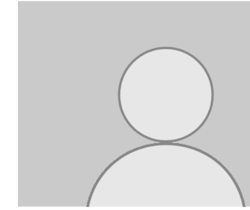
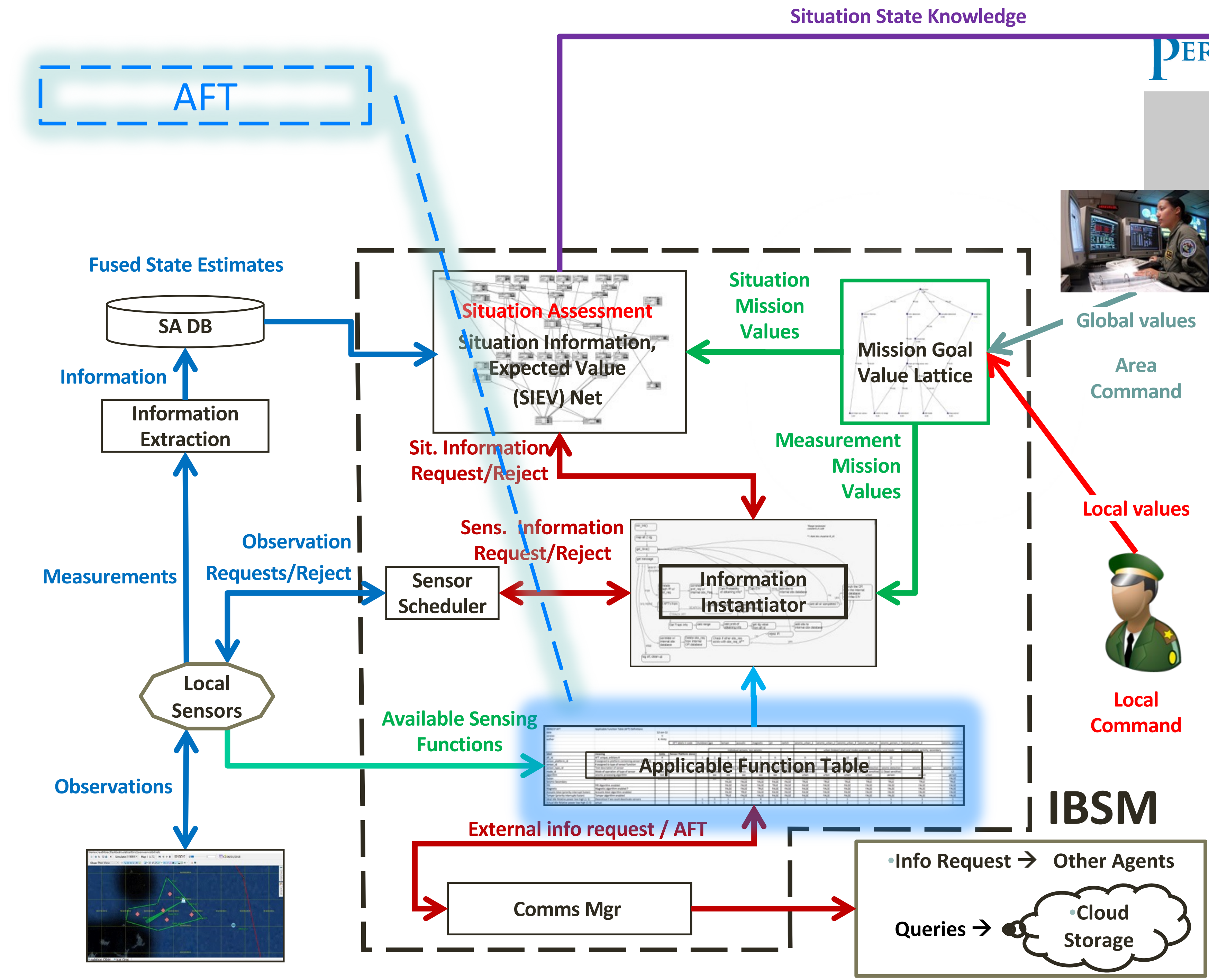


- The information instantiator converts ***situation information needs to sensor observation requests***
  - ***Does not care which sensor*** performs the observation function
  - ***Does not care why*** SIEV-net wants the observation
- ***Downselects*** from the applicable function table (AFT) to a set of ***admissible functions*** (AF) which can satisfy the situation information request
- Computes expected ***sensor information value rate,*** $\boldsymbol{EI_{sen}VR}$ for admissible applicable sensor functions and orders them
  - Selects ***the sensor function*** with the highest $EI_{sen}VR$
  - Sends ***observation request*** to the sensor ***scheduler***
  - If observation request rejected by sensor scheduler, issues next feasible observation request
- If no observation request is feasible, II sends ***info request reject*** back to SIEV-Net

Sensor Functions *vs* Sensor Observations



- The ***information instantiator*** needs to decide which ***sensor function*** produces the maximum ***sensor EIVR*** without regard to which actual sensor performs that function or how it does it
- ***Sensor scheduling*** of actual observations is done separately
- Sensors have capabilities which are defined by their ***operating modes or functions***
  - A sensor may be capable of performing more than one function
  - More than one sensor may be capable of performing the same function
- Each sensor function is a separate entry in AFT
  - More than one sensor may map to a single AFT entry
- Local or remote sensors ***add/remove capabilities*** from AFT as they become available, unavailable, degraded, or enhanced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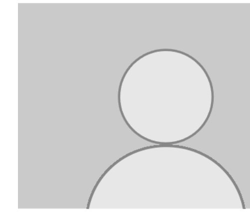
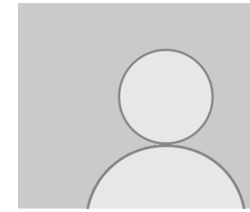
IBSM Component: Applicable (Sensor) Function Table



- Sensors have capabilities which are defined by their sensing functions
- Some sensor functions can be accomplished by multiple sensors each of which has ***different operational parameters*** resulting in ***different*** $\boldsymbol{EI_{sen}VR}$
  - A sensor may be capable of performing more than one sensor function (e.g., range, bearing, Doppler using radar)
  - More than one sensor may be capable of performing the same function (e.g., Ka-band, X-band, LIDAR)
- Local or remote sensors can add, remove or update their capabilities in AFT based on changing capabilities (*e.g.,* environmental effects, failures) enabling ***graceful system degradation***
- External collaborators' capabilities (*e.g.,* wingman, individual UAVs in swarm) are entries in AFT

Applicable (Sensor) Function Table



- Each sensor is required to have its AFT entry described in ***sensor modeling language*** (SML) which ***facilitates the use of new sensors***
- When a sensor is ***brought on-line***, it communicates its AFT functions to IBSM which uses it to populate AFT database
  - Includes operational parameters, e.g., ROC, observation duration
  - A "bus", e.g., a UAV, can fly with different sensors on different missions without a change in sensor manager
- The applicable function table (AFT) is not simply a listing of sensors, but rather a ***dynamic database of sensor functions*** which can be performed by the available sensors
- The AFT is dynamic and allows for ***graceful degradation*** of sensor system as well as real-time addition of external sensors via communications channel

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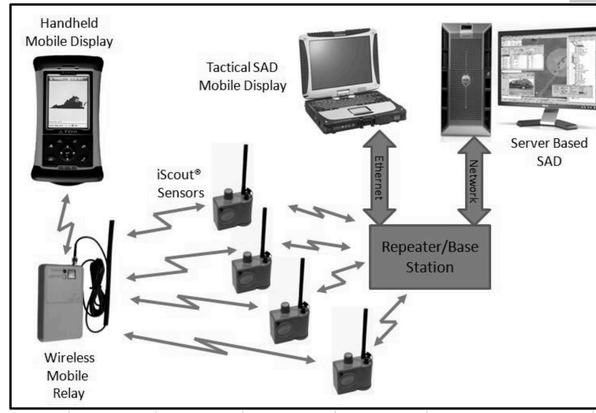
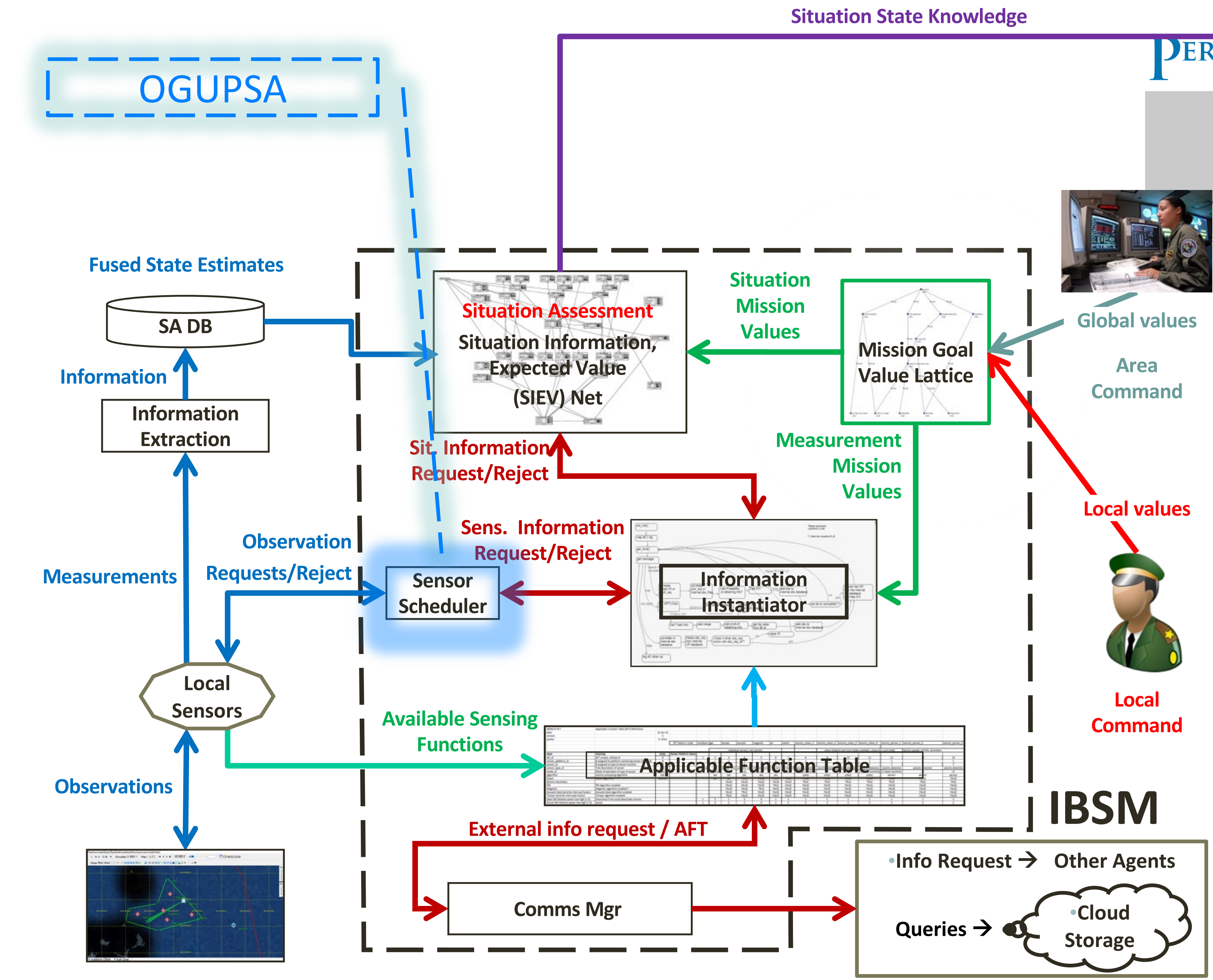
(partial) AFT for Reduced Power COTS Unattended Ground Sensor Network



IBSM/LP AFT	Applicable Function Table (AFT) Definitions																
date		12-Jan-12															
version		5															
author		K. Hintz															
			AFT labels in code	shutdown	gps	tamper	acoustic	magnetic	pir	switch	seismic_urban_1	seismic_urban_2	seismic_urban_3	seismic_urban_4	seismic_person_1	seismic_person_2	seismic_person_3
					individual sensors, non-seismic							urban (indoor) and rural modes available, using only rural mode				seismic people, activity, secondary	
label	**meaning**	**Units**	**Sensor Platform alone**														
aft_id	AFT unique, arbitary #	#		1	2	3	4	5	6	7	8	9	10	11	12	13	14
sensor_platform_id	# assigned to platform containing sensor (iScout #)	#			1	1	1	1	1	1	1	1	1	1	1	1	1
sensor_id	# assigned to type of sensor function	#			1	2	3	4	5	6	7	7	7	7	7	7	7
sensor_type_id	Text description of sensor	text		shutdown	GPS	tamper only	acoustic only	magnetic only	PIR only	Ext Switch	seismic detection	seismic detection	seismic detection	seismic detection	seismic detection	seismic detection	seismic detection
mode_id	Mode of operation of type of sensor	text			position		n/a	n/a	n/a	n/a	L1 (least sensitive)	L2	L3	L4 (most sensitive)	L1 (least sensitive)	L2	L3
algorithm	seismic processing algorithm	text			xxx	xxx	xxx	xxx	xxx		urban	urban	urban	urban	person	person	person
fusion	fusion algorithm	boolean			xxx	xxx	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Seismic Secondary						FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
PIR	PIR Algorithm enabled					FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Magnetic	Magnetic algorithm enabled ?					FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Acoustic blast (priority interrupt fusion)	Acoustic blast algorithm enabled					FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Tamper (priority interrupts fusion)	Tamper algorithm enabled					TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Ideal Idle Relative power low-high (1-5)	theoretical if we could deactivate sensors			1	5	1	2	4	1	1	1	1	1	1	1	1	1
Actual Idle Relative power low-high (1-5)	actual			1	5	2	2	4	2	2	2	2	2	2	2	2	2



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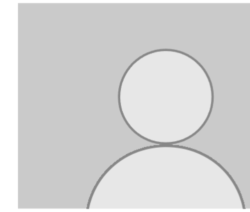
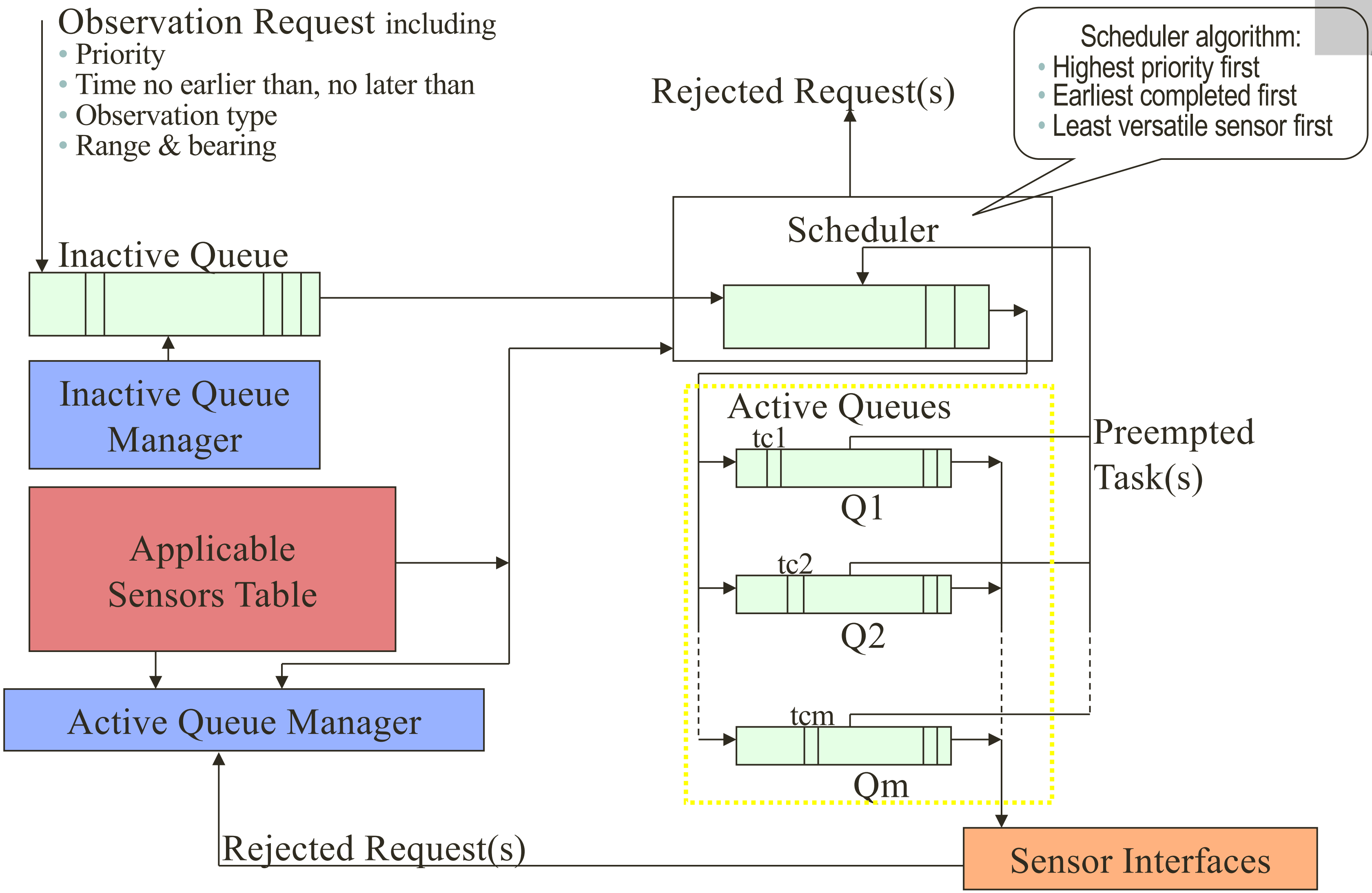
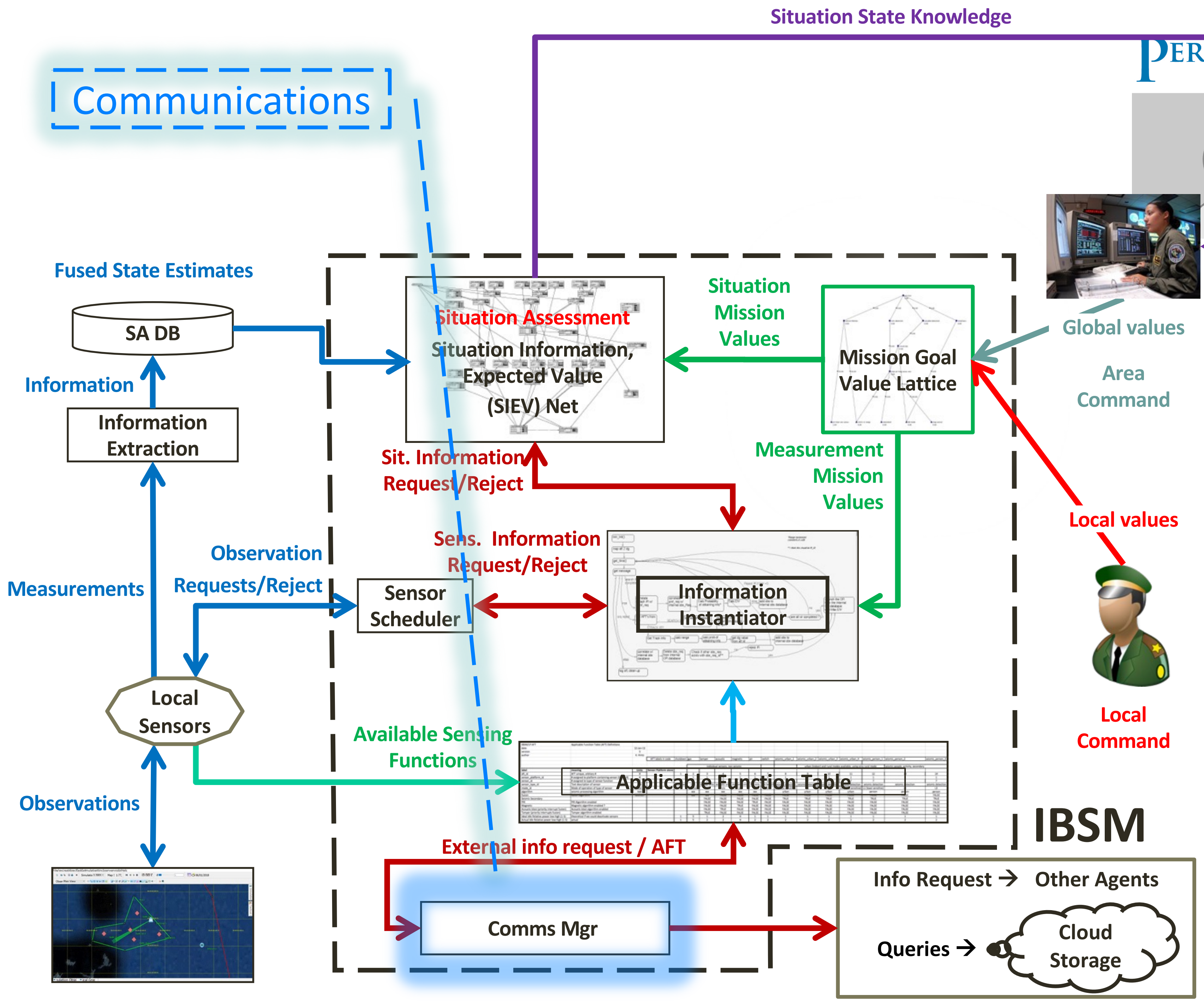
IBSM Component: Sensor Scheduler



- ***Sensor observation requests*** from the information instantiator are sent to an ***on-line, greedy, urgency-driven, preemptive scheduling algorithm*** (OGUPSA)
- Since more than one sensor may be able to perform a sensing function which satisfies the observation request, OGUPSA routes the request to the sensor queue for the ***least versatile sensor*** which can make that observation
- OGUPSA may ***preempt*** previously queued observations if they are of lesser value
- These are general requirements and any suitable sensor scheduler may be used

OGUPSA


Observation Request including
Priority
Time no earlier than, no later than
Observation type
Range & bearing
Rejected Request(s)
Scheduler algorithm:
Highest priority first
Earliest completed first
Least versatile sensor first
Scheduler
Inactive Queue
Inactive Queue Manager
Applicable Sensors Table
Active Queue Manager
Active Queues
tc1
Q1
tc2
Q2
tcm
Qm
Preempted Task(s)
Rejected Request(s)
Sensor Interfaces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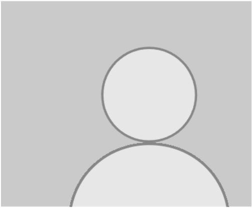
Mission Goal Value Lattice
Global values
Area Command
Sit. Information Request/Reject
Measurement Mission Values
Sens. Information Request/Reject
Information Instantiator
Local values
Local Command
Applicable Function Table
IBSM
External info request / AFT
Comms Mgr
Info Request → Other Agents
Queries →
Cloud Storage

Communications Manager



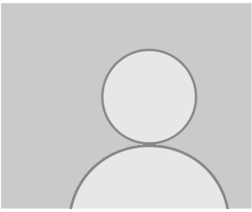
- The communications manager allows for sending/receiving inbound and outbound situation ***information requests*** to/from collaborating and friendly platforms
  - e.g., tracks, search region descriptions, request status, PMF
- Allows for sending/receiving ***AFT entries*** to/from collaborating and friendly platforms
- Transmitting and receiving goals and goal values
  - Allows for ***receiving shared goals*** from higher authority
  - Allows for ***transmitting actual goal values*** of shared goals to higher authority
- Acquiring data to update unmanaged evidence nodes

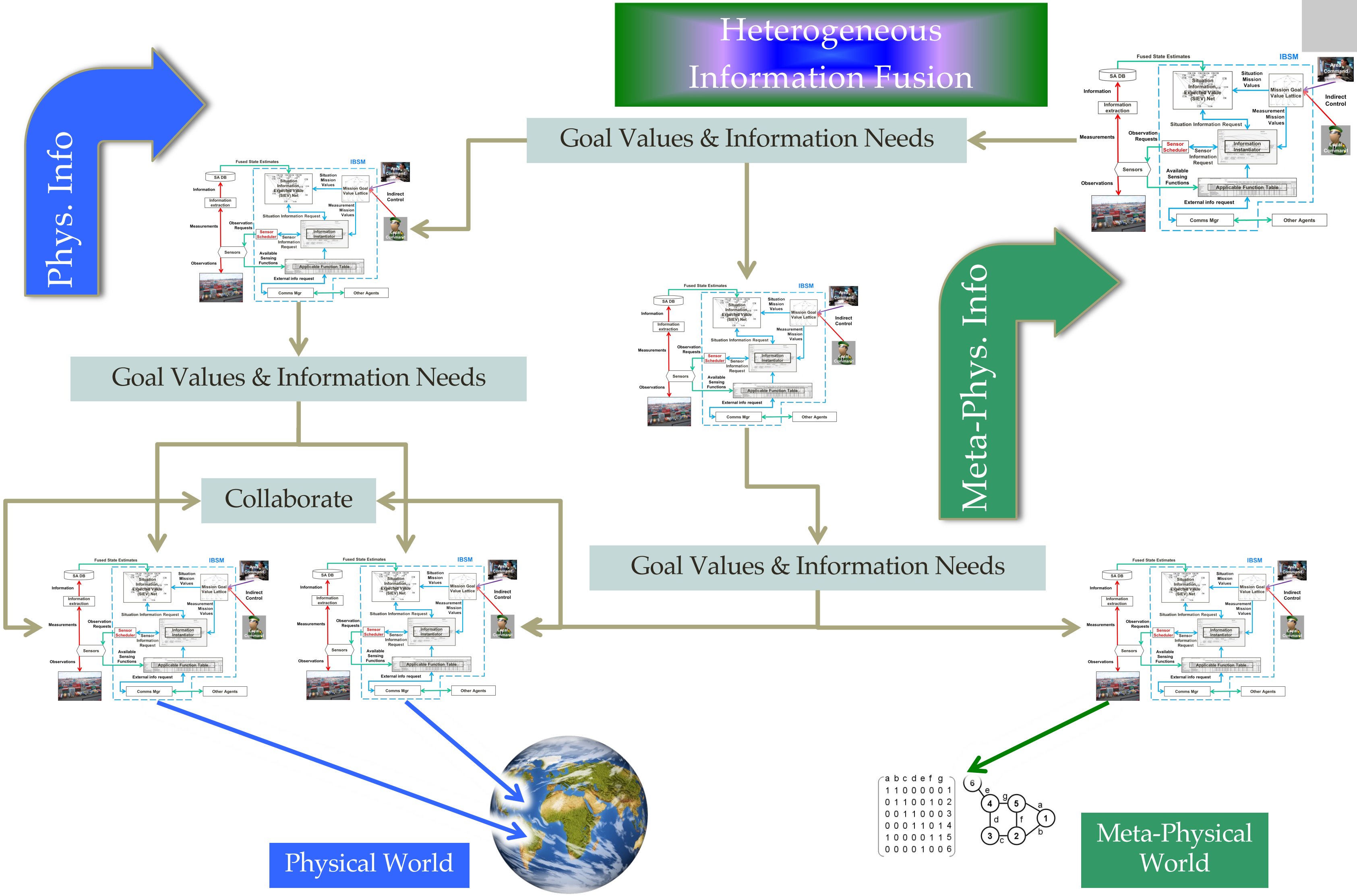
Utilizing Replicated IBSM: Networked Hard/Soft Fusion

- ***IBSM concept is platform independent*** and can be used for theatre information acquisition as well as individual sensor platform management
- One ISR layer's sensors is another layer's squadron is another layers aircraft, …
- ***HOL operation*** is exercised through transmission of shared goals among layers and information requests

PERQUIRE RESEARCH

Scalability Demonstrated in Networked IBSM, Hard/Soft Fusion with Implicit Collaboration





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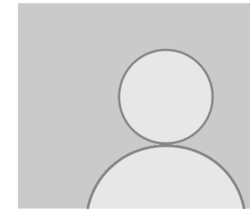
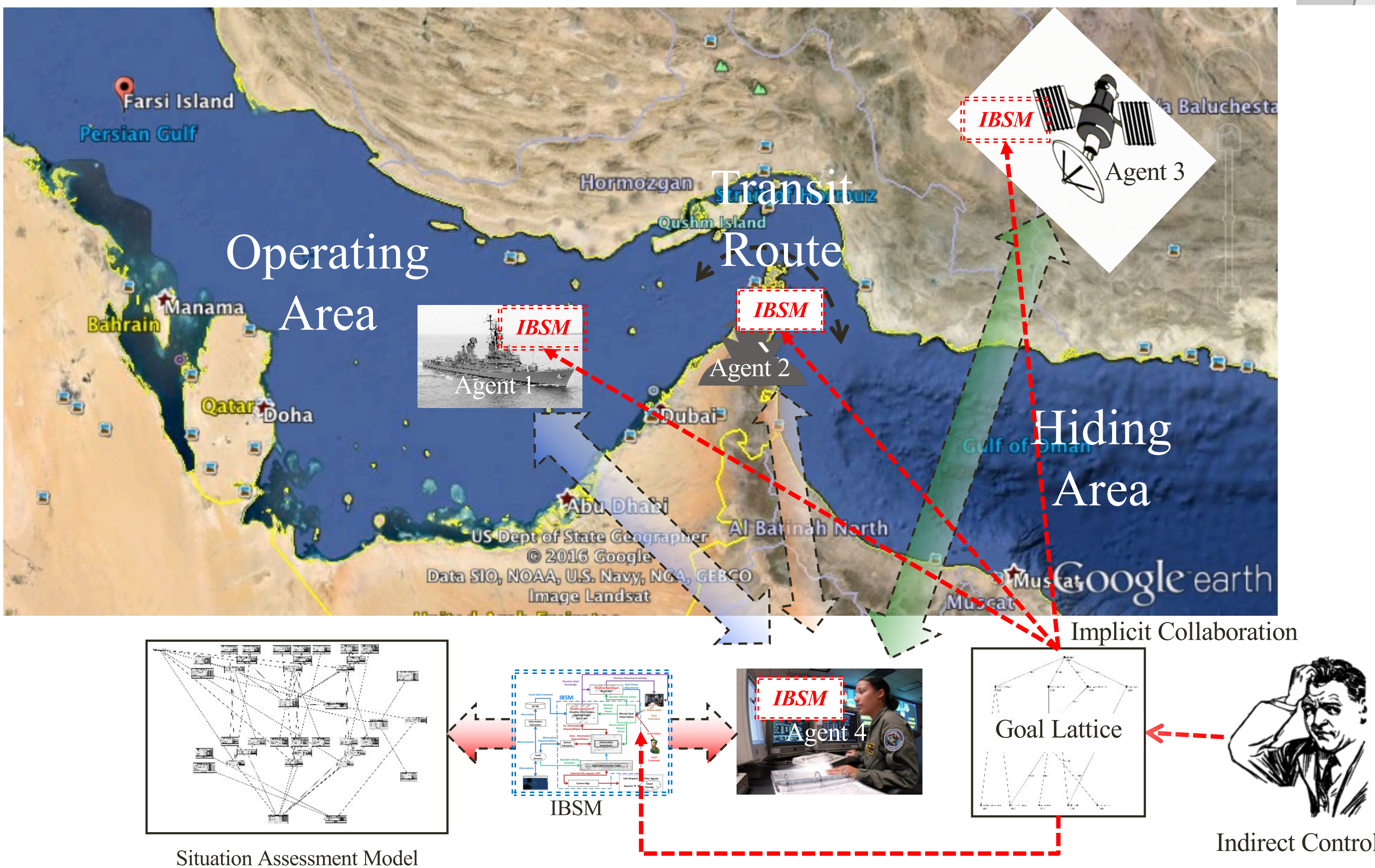
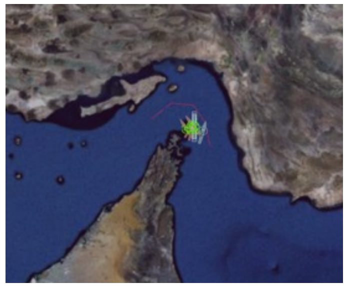
Reification of the Notional Spatial Model

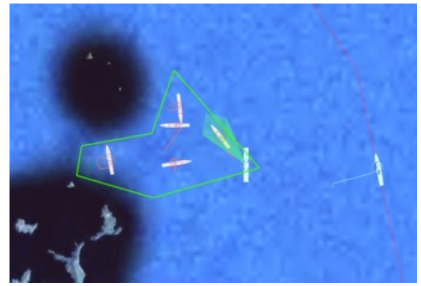


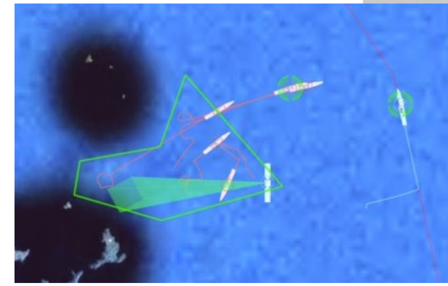


PERQUIRE RESEARCH

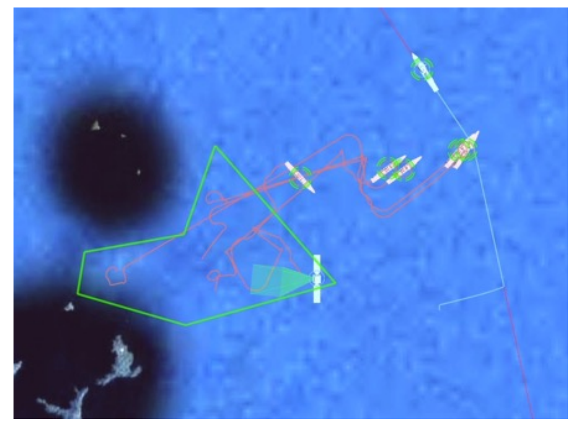
St. of Hormuz Scenario, Overhead Surveillance, Simulated in MAK, VR Forces

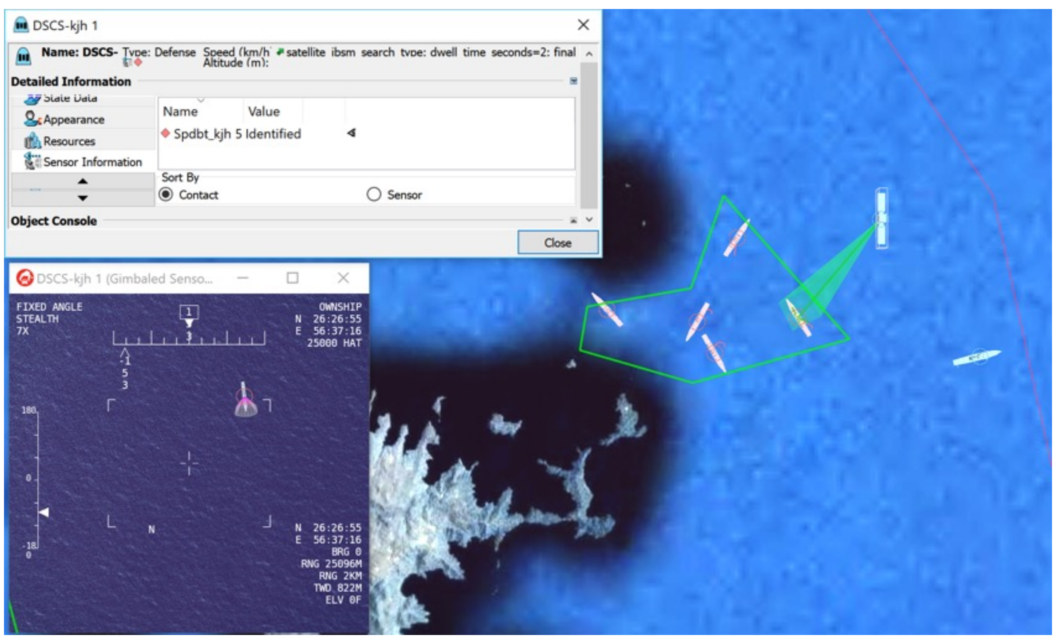


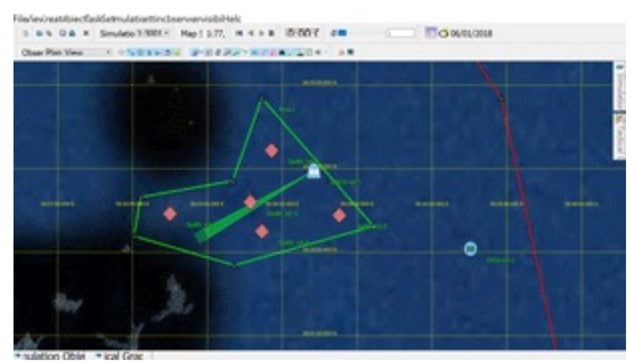


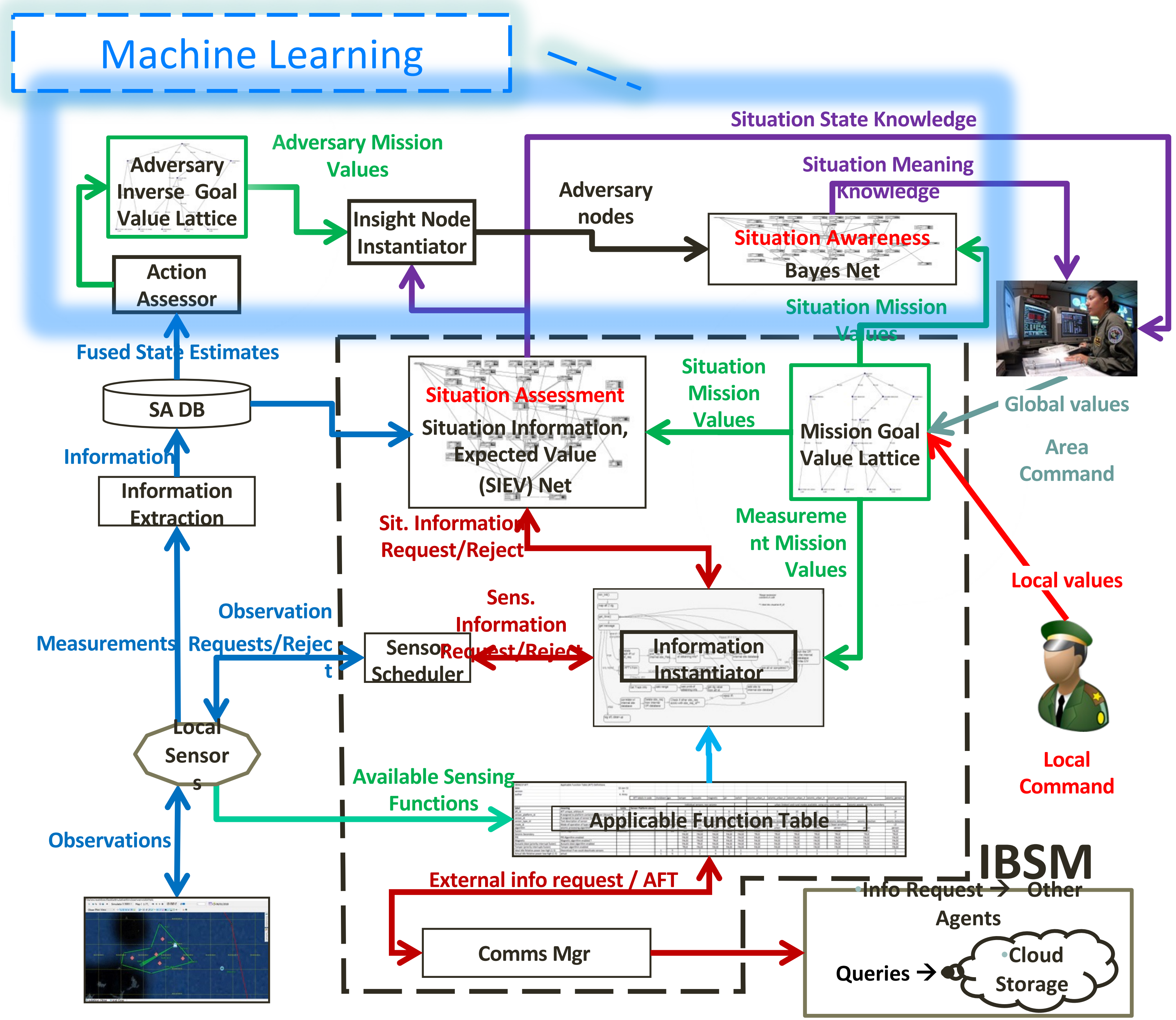


Speedboats random movement in area converting to attacking transiting DDG



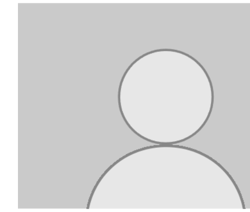






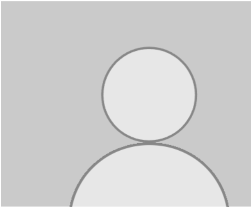
Machine Learning
Situation State Knowledge
Adversary Mission Values
Adversary Inverse Goal Value Lattice
Insight Node Instantiator
Adversary nodes
Situation Meaning Knowledge
Situation Awareness Bayes Net
Action Assessor
Situation Mission Values
Fused State Estimates
SA DB
Situation Assessment
Situation Information, Expected Value (SIEV) Net
Situation Mission Values
Mission Goal Value Lattice
Global values
Area Command
Information
Information Extraction
Sit. Information Request/Reject
Measurement Mission Values
Local values
Sens. Information Request/Reject
Observation Requests/Reject
Measurements
Sensor Scheduler
Information Instantiator
Local Sensors
Local Command
Available Sensing Functions
Applicable Function Table
Observations
IBSM
External info request / AFT
Info Request → Other Agents
Comms Mgr
Queries →
Cloud Storage

Current Interest: Machine Learning in IBSM



Two areas where machine learning (ML) can be applied to IBSM

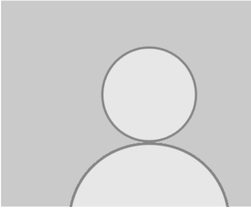
- Real-time analysis and modification of mission goal values to improve overall performance
- Inclusion of an adversary behavioral model
  - ***Action assessor***
  - ***Inverse*** adversary mission ***goal-value lattice***
  - Adversary ***insight-node*** instantiator
  - Situation ***awareness*** Bayesian Network



ML components

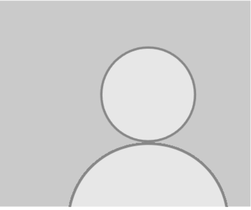
- Action assessor ***evaluates the fused state estimates*** to determine to what higher level adversarial goals they may contribute
- Inverse goal-value lattice propagates real adversarial action up to ***determine the relative higher level goal values of the adversary***
- Insight node instantiator ***creates new nodes for the situation awareness BN*** so that these hypothetical behaviors can be analyzed by acquiring more information as determined by the situation awareness EIVR
- Situation awareness Bayesian Network is comprised of ***possible future actions by the adversary*** and makes the ***probability of these actions*** available to the analyst

Summary: IBSM Is a ***Satisficing Solution*** To Multiplatform Heterogeneous Real-Time Sensor & Mission Management



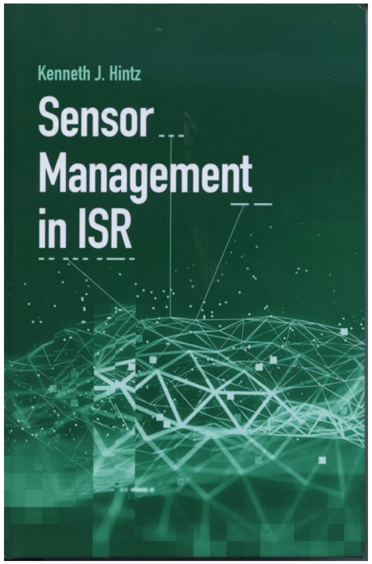
- IBSM is a system which can be ***encapsulated in a container***, instantiated multiple times in parallel either in the cloud or locally, and needs ***only the goal lattice to be particularized*** for the platform and mission.
- ***Real-time, scalable, collaborative system*** from individual platform sensor management to management of battlespace reconnaissance assets
- Based on ***maximizing expected information value rate (EIVR)*** to ***minimize uncertainty*** in the ***world model*** while ***maximizing mission value***
- Provides the ***highest valued, lowest uncertainty, context sensitive, situation estimate*** from which to make command decisions
- ***Closed loop, indirect, and context sensitive*** control through the use of interacting, mission oriented goal lattice and HOL

Summary: IBSM Is a ***Satisficing Solution*** To Multiplatform Heterogeneous Real-Time Sensor & Mission Management



- ***Dynamically reconfigurable*** through use of ***applicable*** (sensor) ***function table***
- ***Information instantiator*** allows for ***one sensor management model*** to be the framework for multiple platforms and hierarchical levels of resource management
- Sensors can be added or removed in real-time without redesigning the system which provides for ***graceful degradation and robust behavior in dynamic, stressing environments***
- Autonomous systems behave with ***subservient autonomy***

Questions?



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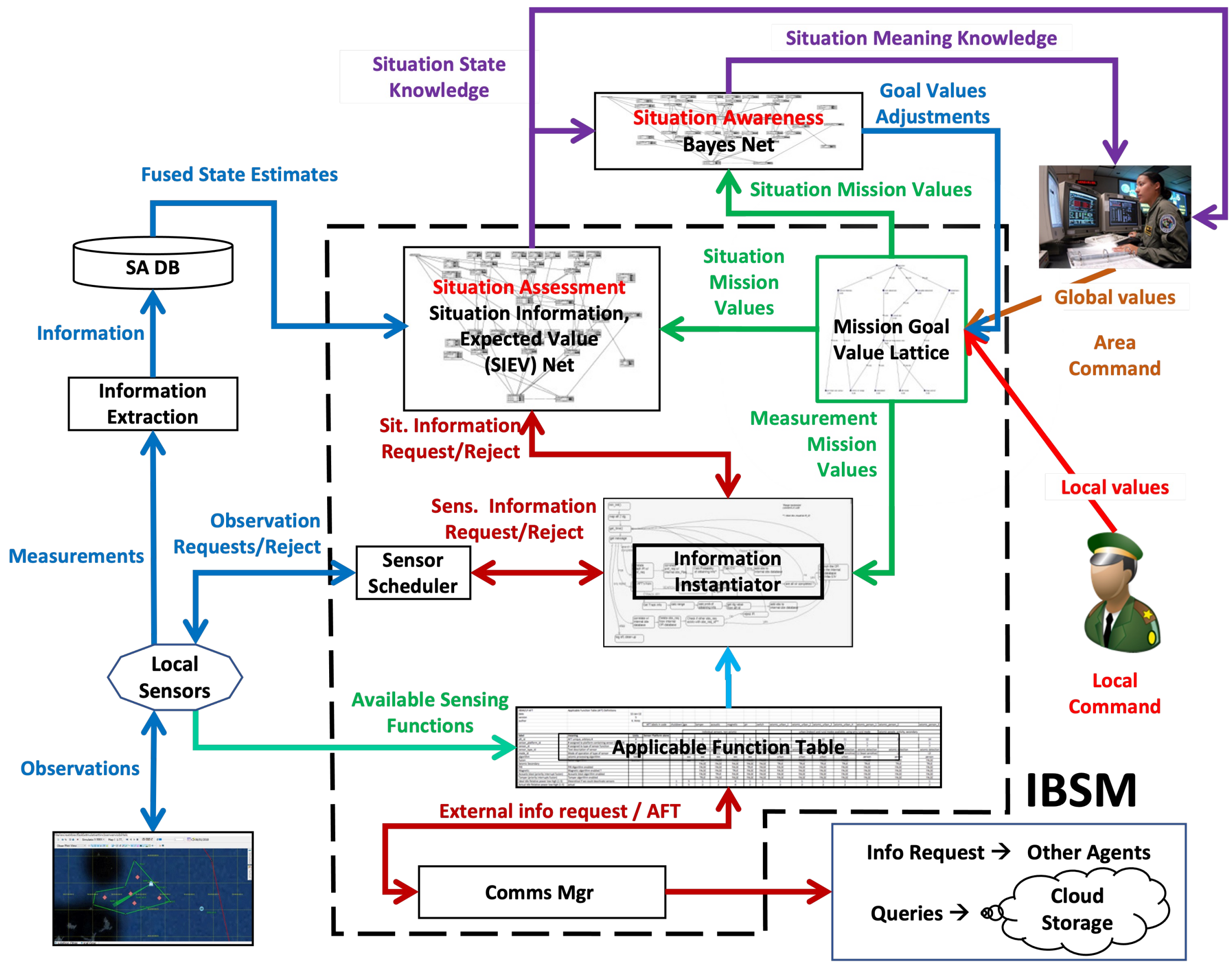

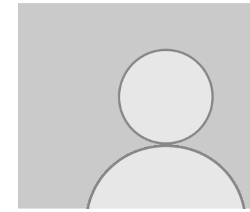

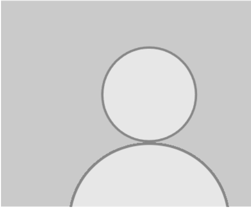

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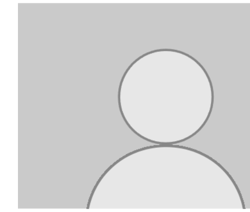

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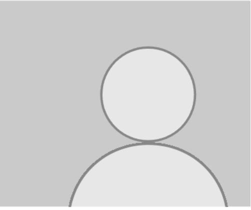

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