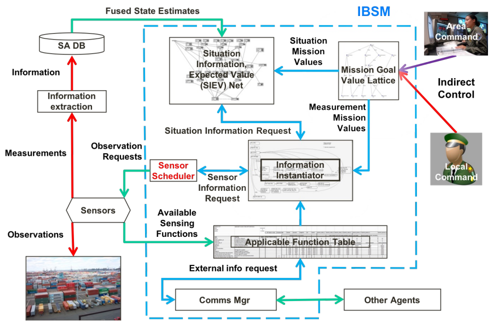
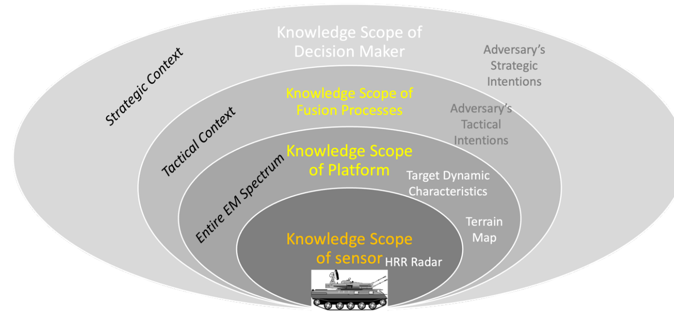


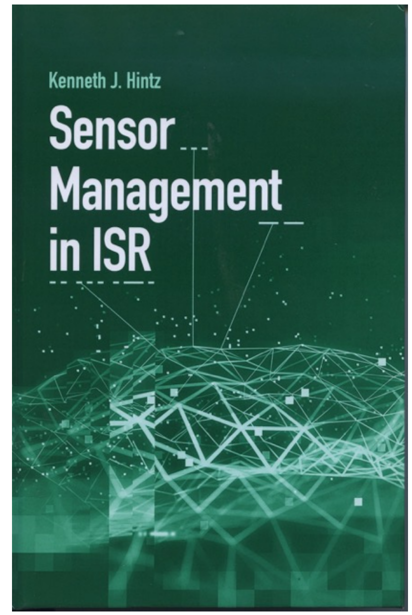


Introduction to Sensor Management
and
Knowledge Aggregation, Representation, Processing, and Presentation (KARPP)

Dr. Kenneth Hintz
Mechanical and Aerospace Engineering Dept.
SUNY at Buffalo
khintz2@buffalo.edu
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
- 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



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

Tutorial Outline: Historical basis for SM (~10)

- Pre WW-II
- Cold war era
- Vietnam era
- Current asymmetric warfare & 911
- Network Centric Warfare

Tutorial Outline: Fundamental Concepts (~20)

- JDL Model
- Definitions
- Distinction between scheduling & management
- Motivation for sensor management
- Types of SM systems

Tutorial Outline, Issues in SM (~20)

- Resource constrained
- Multidisciplinary
- World models
- Route planning
- Redundant coverage
- Data fusion or decision fusion
- Centralized, distributed, or hybrid management
- Design considerations

Tutorial Outline: SM Theoretical approaches (~10)

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

Tutorial Outline: IBSM (~30)

- 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

Tutorial Outline: KARPP (~20)

- Knowledge Aggregation, Representation, Processing, and Presentation (KARPP)
- A new approach expanding sensor management to knowledge acquisition from the highest levels of decision making to the acquisition of knowledge from a sensor/database/network

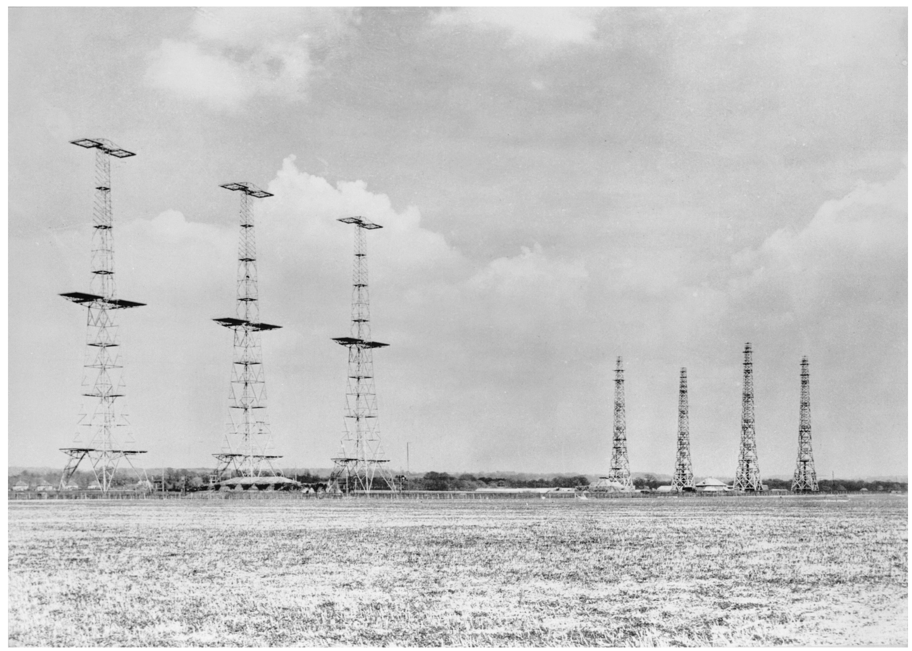
Tutorial Outline: Historical basis for SM (~10)

- Pre WW-II
- Cold war era
- Vietnam era
- Current asymmetric warfare & 911
- Network Centric Warfare

World War II (WW II)

- **Pre-WW-II**: the transfer of information from one place to another was limited to
  - Physical transport
  - 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

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

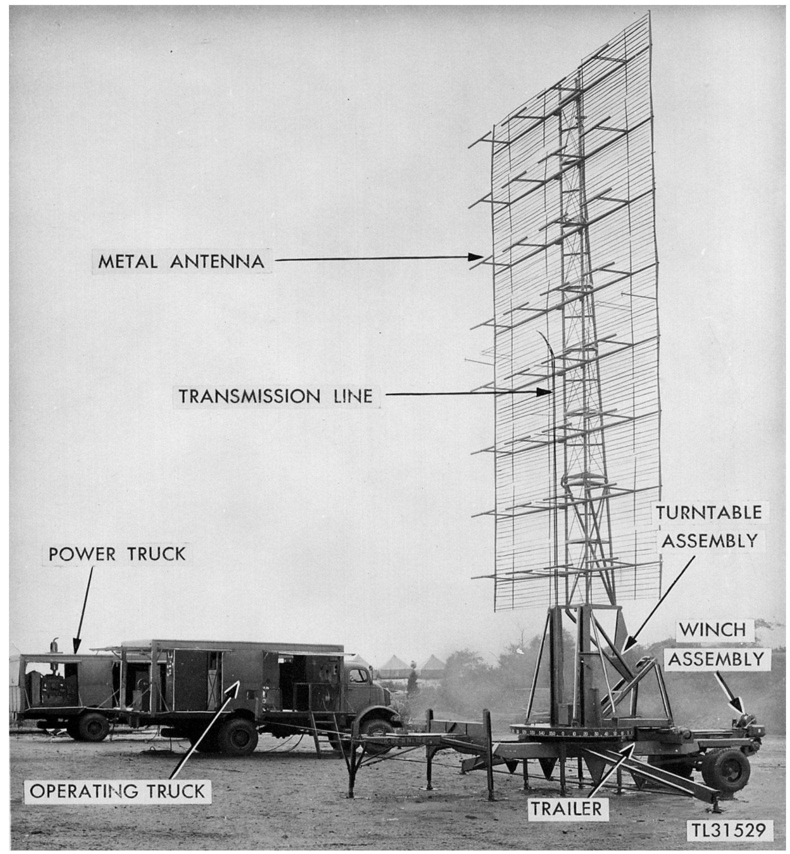


World War II (WW II)

- ***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

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]
- **Integrated multiple heterogeneous sensors** on individual platforms performing local situation assessment and technical intelligence collection (ELINT, COMINT, SIGINT)
  - Development of U-2, SR-71, EP-3E, etc. and reconnaissance satellites

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***

Network Centric Warfare (NCW)*

"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 Changing Roles Of Battlespace Entities*

- Network Centric Warfare (NCW)

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

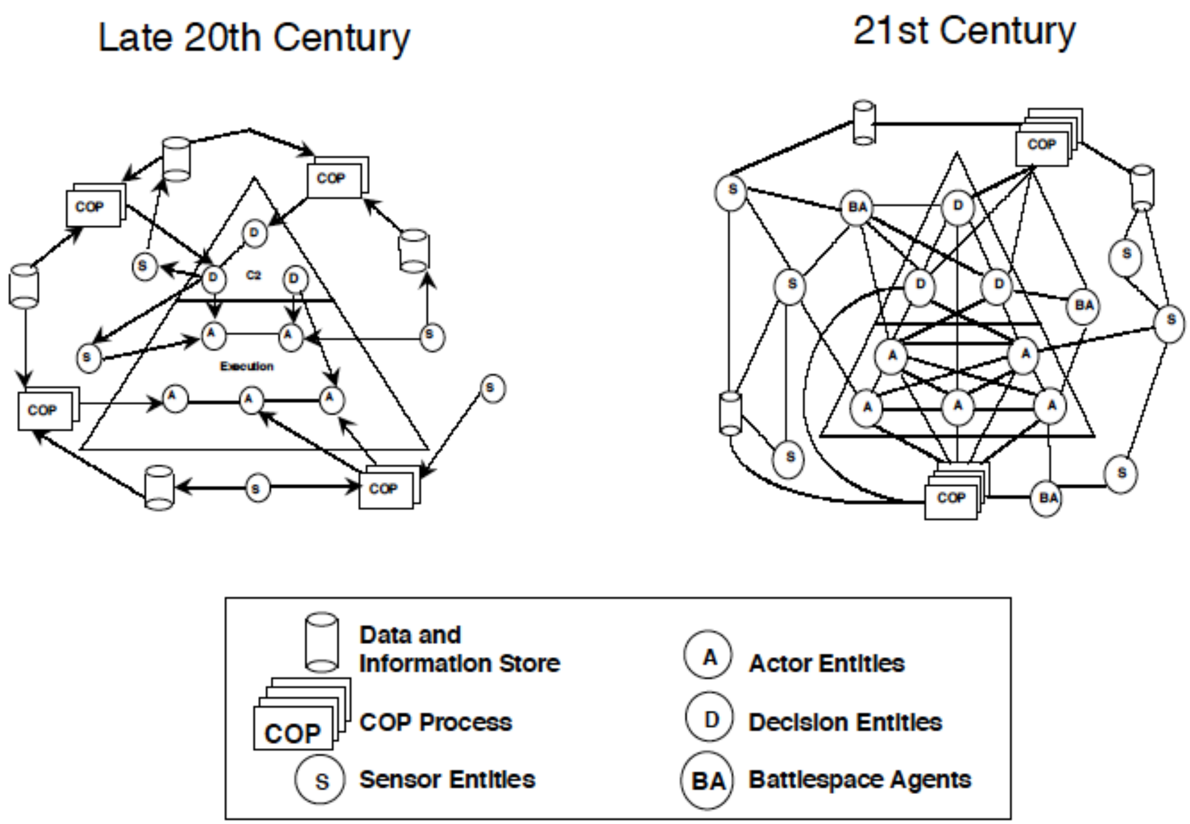


Figure 17. Roles of Battlespace Entities

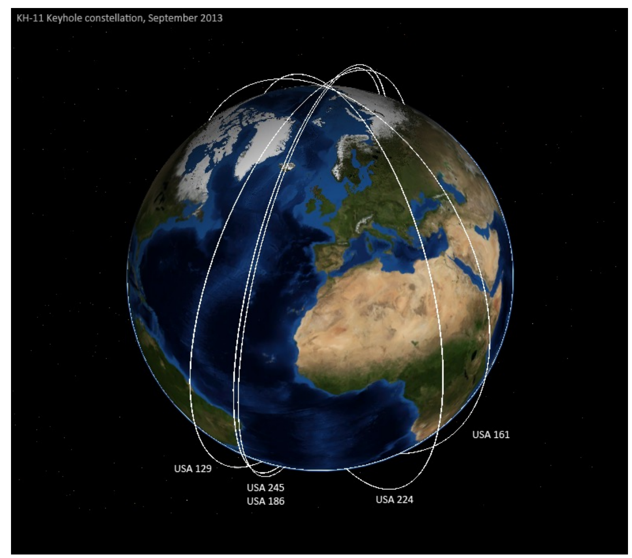
* [Alberts, *et al.*, 15]

Information Centric

- ***Platform is not important, the knowledge 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 valuable, 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

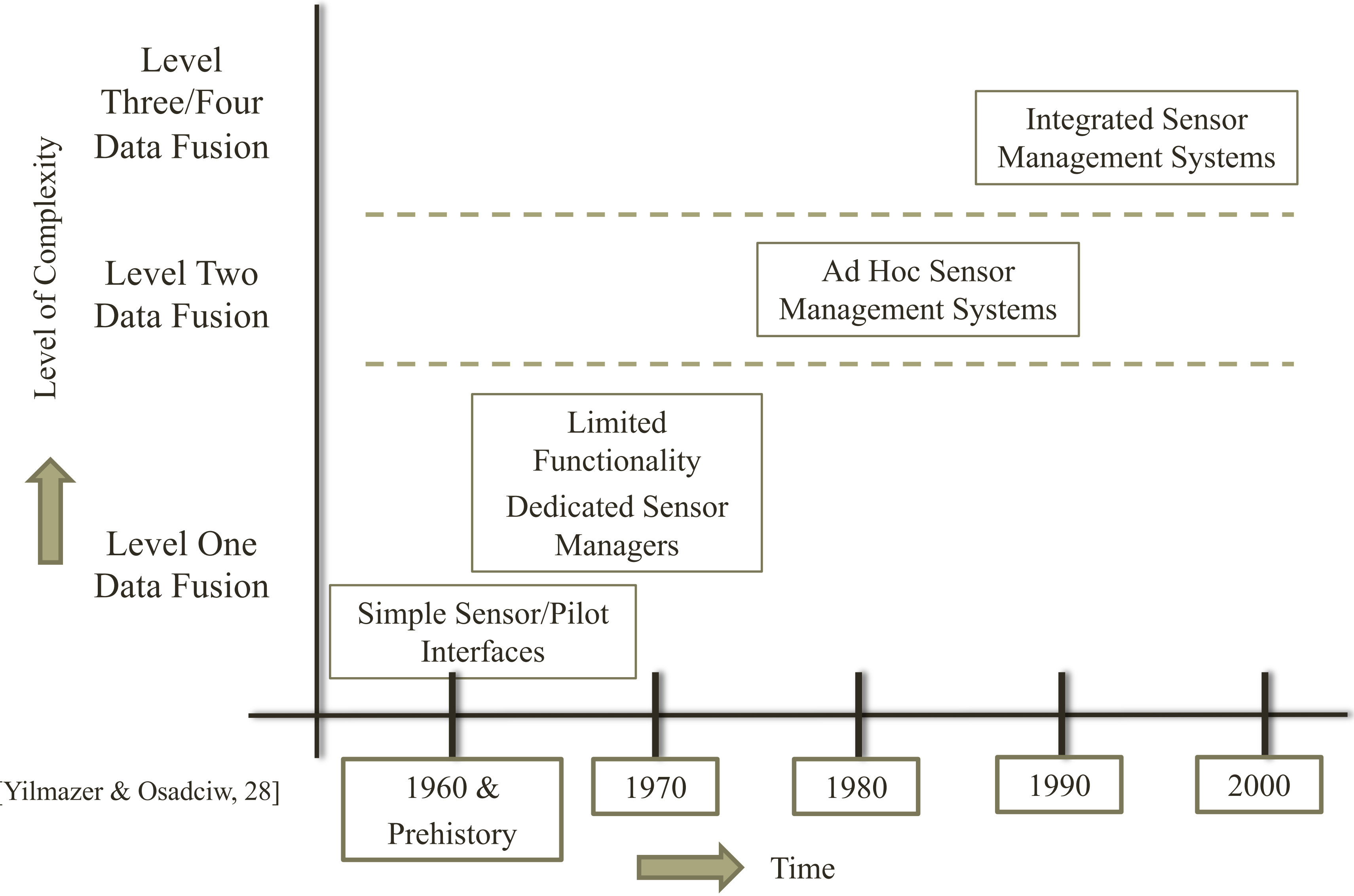
Beginnings Of Networking: Homogeneous Sensors

- **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



Timeline of R&D in SM *

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



* [Yilmazer & Osadciw, 28]

Tutorial Outline: Fundamental Concepts (~20)

- JDL Model
- Definitions
- Distinction between scheduling & management
- Motivation for sensor management
- Types of SM systems

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

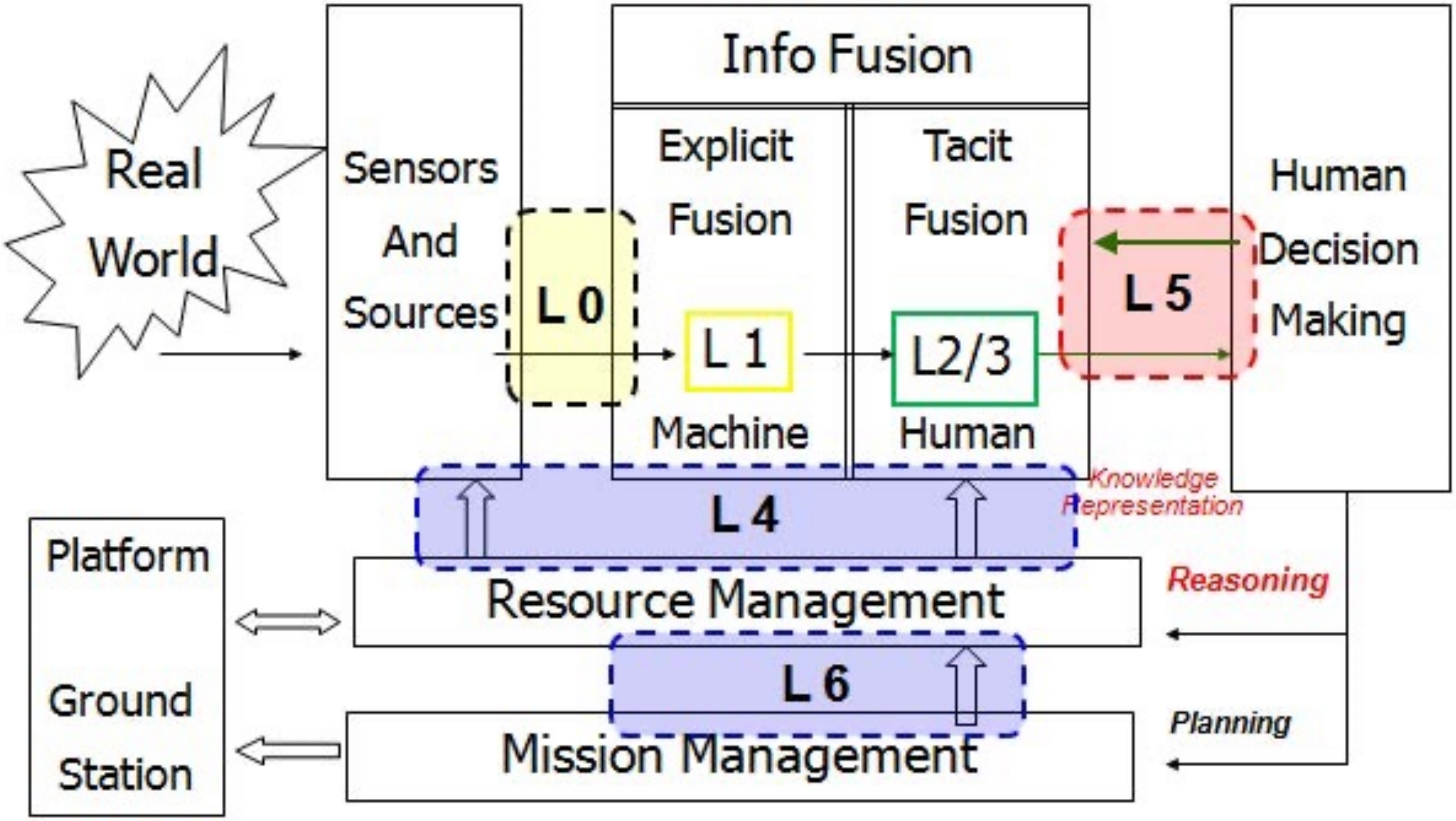
* [Blasch 1]

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]

Relationship of SM to JDL Data Fusion Model *



* [Blasch 1]

Elements of Sensor Management

- ***Control*** of the knowledge gathering activities [Malhotra, 2]
- to accomplish ***specific mission objectives*** [Musick & Malhotra, 3]
- using ***automatic generation of appropriate tasks*** [Shea *et al*., 4]
- in a ***dynamic and uncertain environment*** [McIntyre, 5] [Ng & Ng, 6]

Prescriptive View of Sensor Management

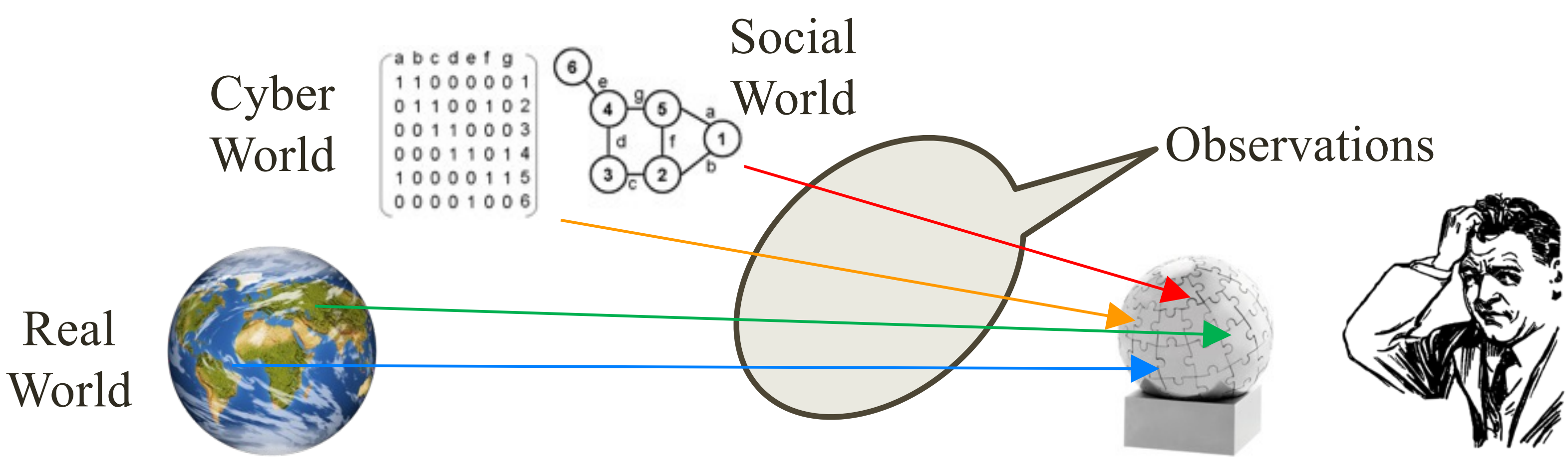
- View sensors as a ***communications channel*** which transfers ***mission-valued information*** from the real world into a mathematical model of that world for ***use by decision makers***
- The goal of sensor management is to ***maximize the expected information value rate*** (EIVR) of data through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

Communications System View of Sensors

PERQUIRE RESEARCH

University at Buffalo
The State University of New York

- ***Knowledge***, not data, is the *raison d'etre* for a sensing system
- More importantly, ***mission-valued*** knowledge is the goal
- The purpose of a sensor system is ***the transfer of knowledge from the real (physical, cyber, or social) world to a mathematical model*** of that world
- Decision maker cannot see the ***real world***, but only the ***mathematical representation*** of the real world that results from the combined sensing actions



Basic Data Fusion Definitions
Data, Observation, Sensor, Measurement

- "***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]
- ***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

Information and 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

Situation Assessment *vs* Situation 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 and KARPP

- Need to ***inform situation assessment, and situation awareness***
  - Sensor management informs situation ***assessment***: ***what*** is in the environment
  - KARPP informs 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***

Tutorial Outline, Issues in SM (~20)

- Resource constrained
- Multidisciplinary
- World models
- Route planning
- Redundant coverage
- Data fusion or decision fusion
- Centralized, distributed, or hybrid management
- Design considerations

SM is a Constrained Optimization Problem

PERQUIRE RESEARCH
University at Buffalo
The State University of New York

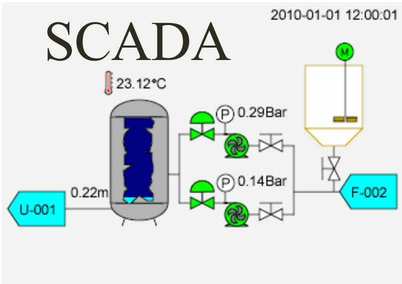
- Sensors ***cannot observe in all directions at the same time***
  - Increase range capability at expense of instantaneous field of view

- 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

Big Data Problem

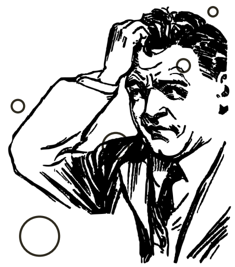
- Big data results from collecting data ***without regard to its information content***
- Sensors are in a ***data rich, information poor*** (DRIP) environment
- Big data problems, the 4 V's
  - **Volume**
  - **Variety**
  - **Velocity**
  - **Veracity**
- Sensor management can ***reduce the quantity 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

Sensor Manager Stochastic Optimization

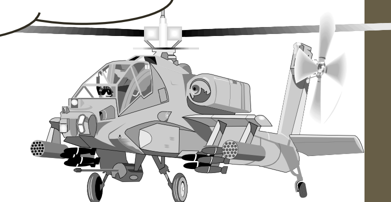


Search: Is anyone else out there?

Track: Who should I track ?

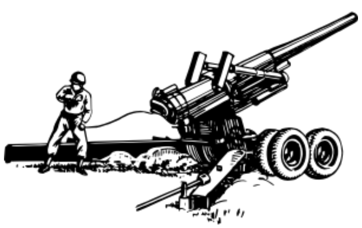


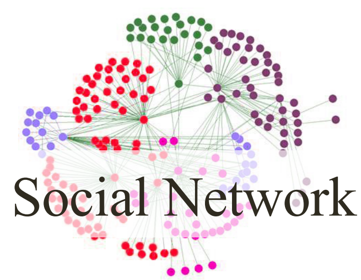
Identify: Who is it?



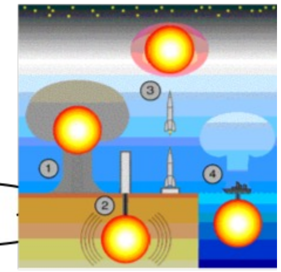
Value: What is the most important mission information?

Constraints: What is the best way to find out?



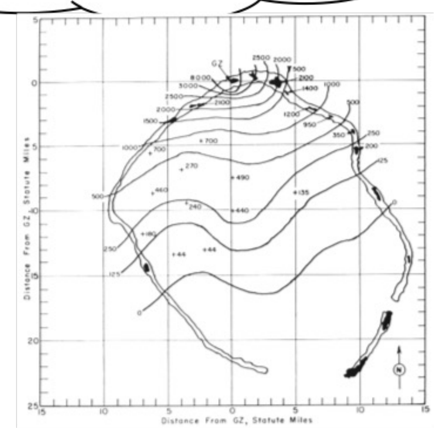


Particular Issues for Nuclear Incident



Identify: What type of nuclear event occurred?

Predict: What will be the area affected?

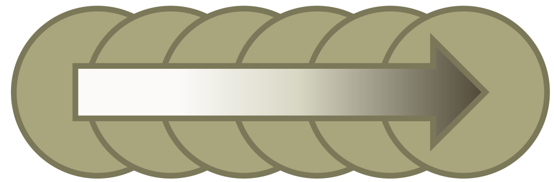


Track: Which way is the radiation cloud moving?

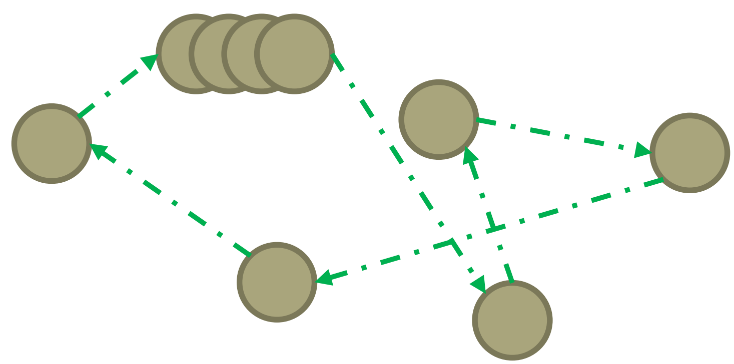
How: Which sensor can acquire a timely, accurate gamma ray count?

http://home.earthlink.net/~ponderthemaunderf/sitebuildercontent/sitebuilderpictures/nuketypes.gif
http://www.archives.gov/education/lessons/fallout-docs/images/atomic-cloud.gif
http://www.radmeters4u.com/cdv715-new.jpg
Ivy mike fallout map, wikimedi commons

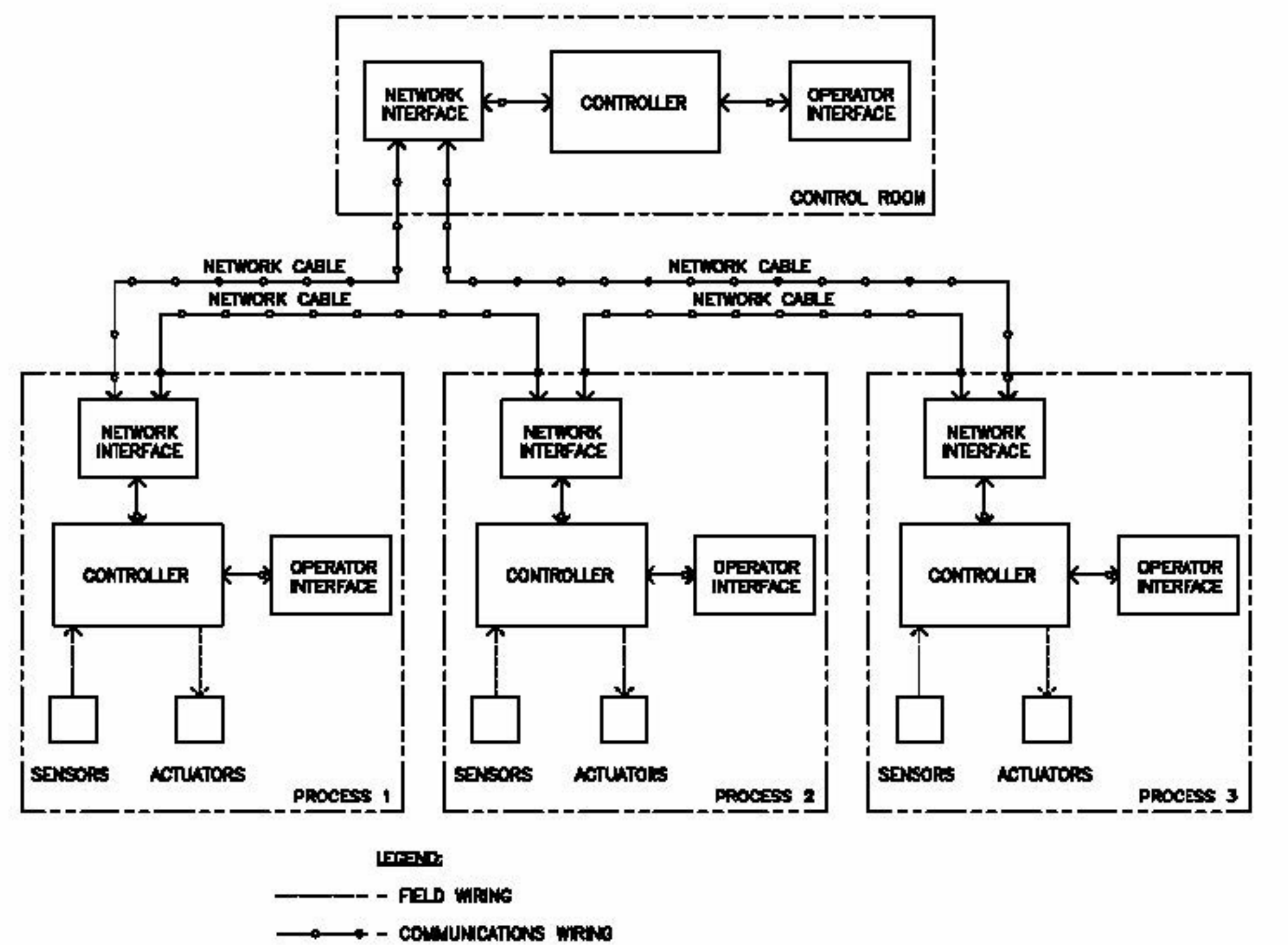
Scheduler *vs* Manager: Performance Index



- 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

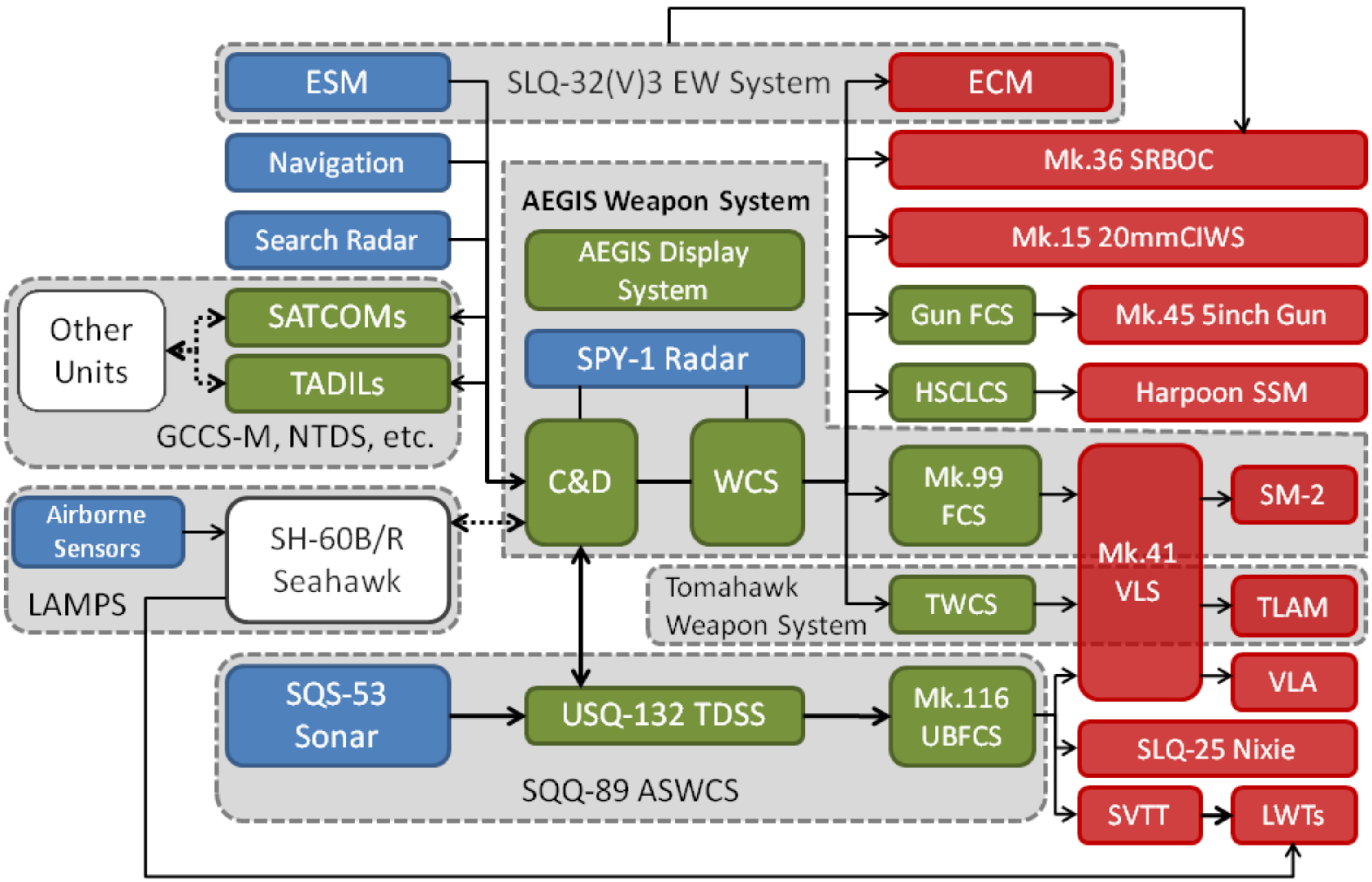


Sensor ***Scheduler*** Example, SCADA*



* [TM 5-601, 22]

AEGIS Combat System, Sensor *Manager*



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

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

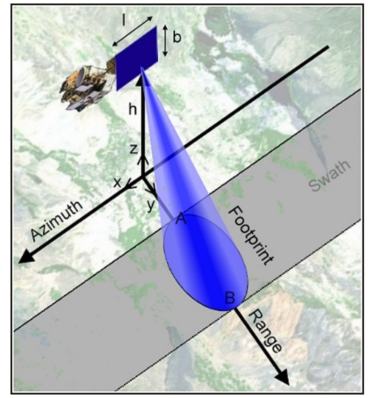
Single Platform Sensor Systems

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



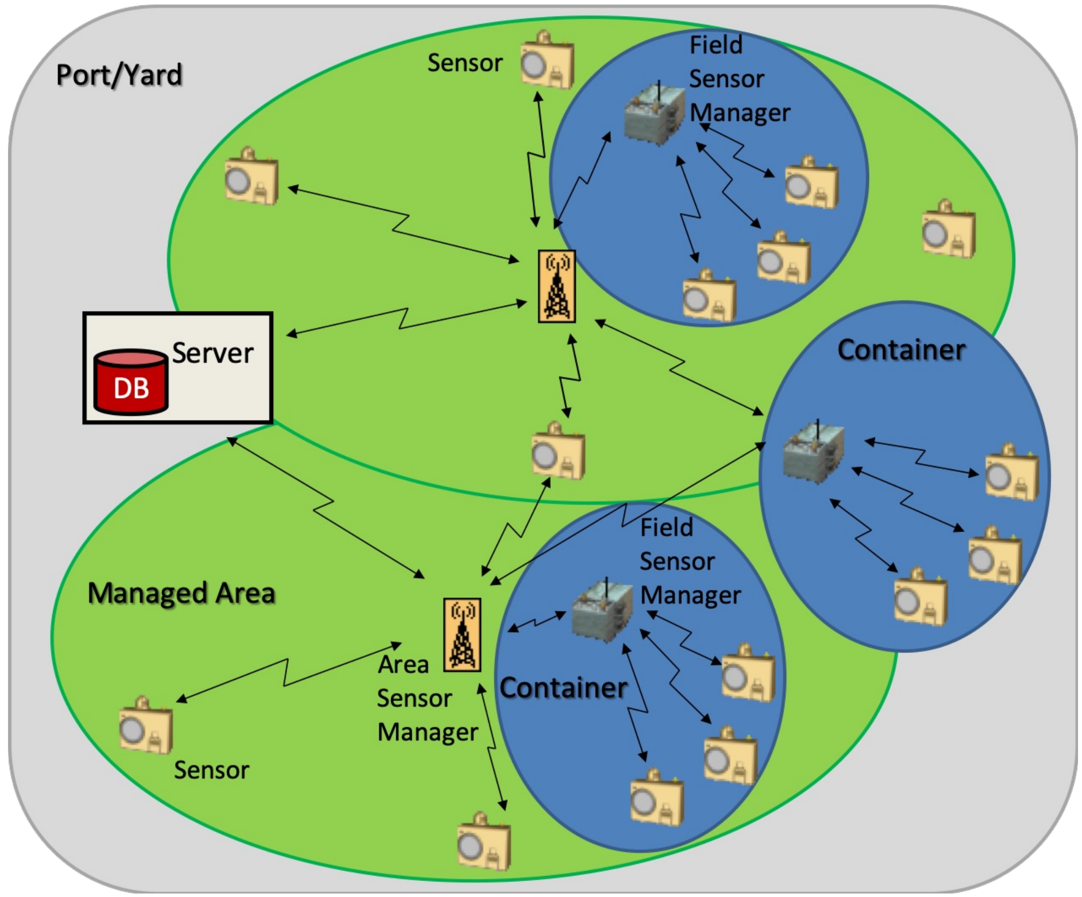
https://commons.wikimedia.org/wiki/Radar#/media/File:Rardiagdrp.jpg

https://upload.wikimedia.org/wikipedia/commons/0/0b/USS_Richard_E_Byrd_%28DDG_23%29_aft.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

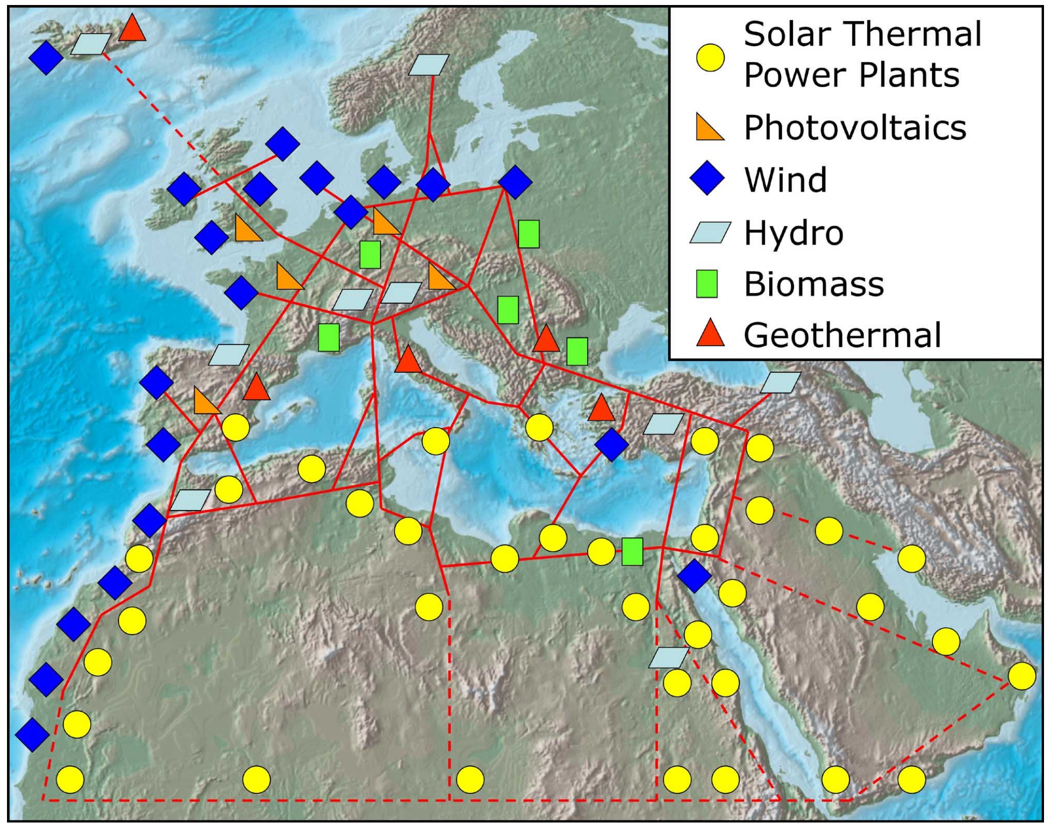


Network of Heterogeneous Electrical Power System Sensors Distributed Over a Large Area

PERQUIRE RESEARCH

University at Buffalo
The State University of New York

- ***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***

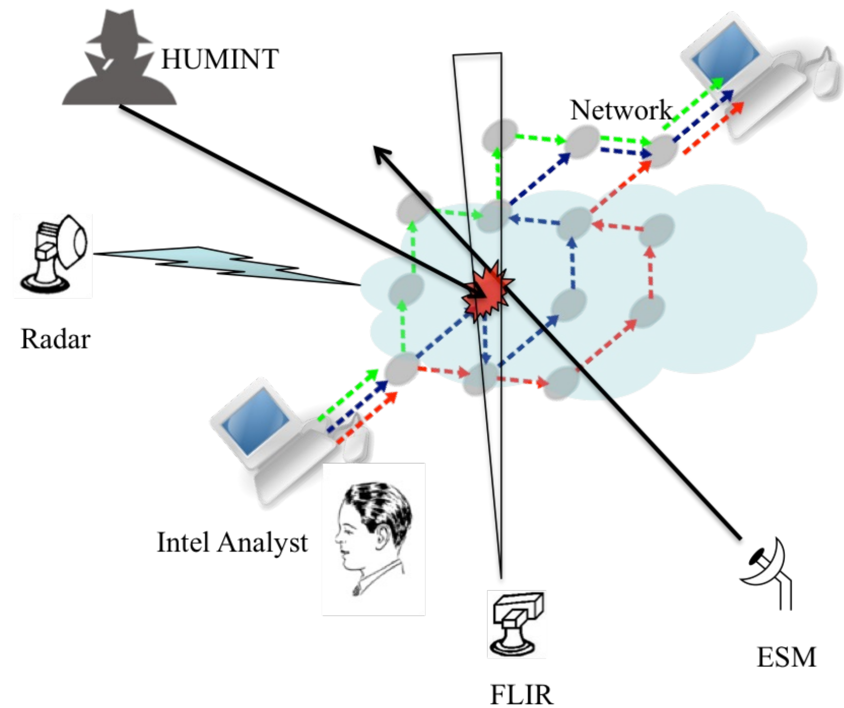


https://commons.wikimedia.org/wiki/File:TREC-Map-en.jpg

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



Design Consideration: HOL rather than HIL

- 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.

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***

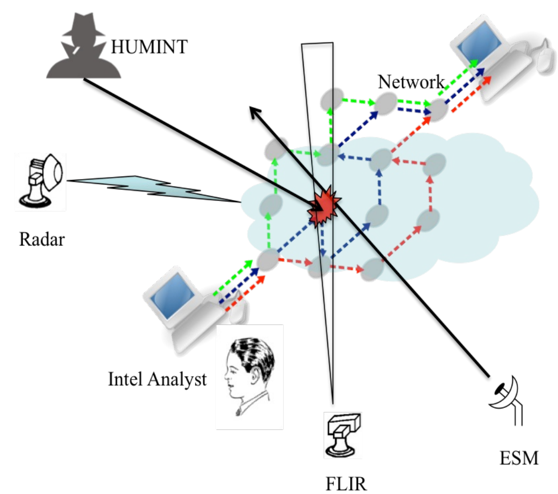
Sensor Management Feasibility Problems

- 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 (LPI) 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 Non-commensurate Data Problem

- Heterogeneous Data Processing
  - 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

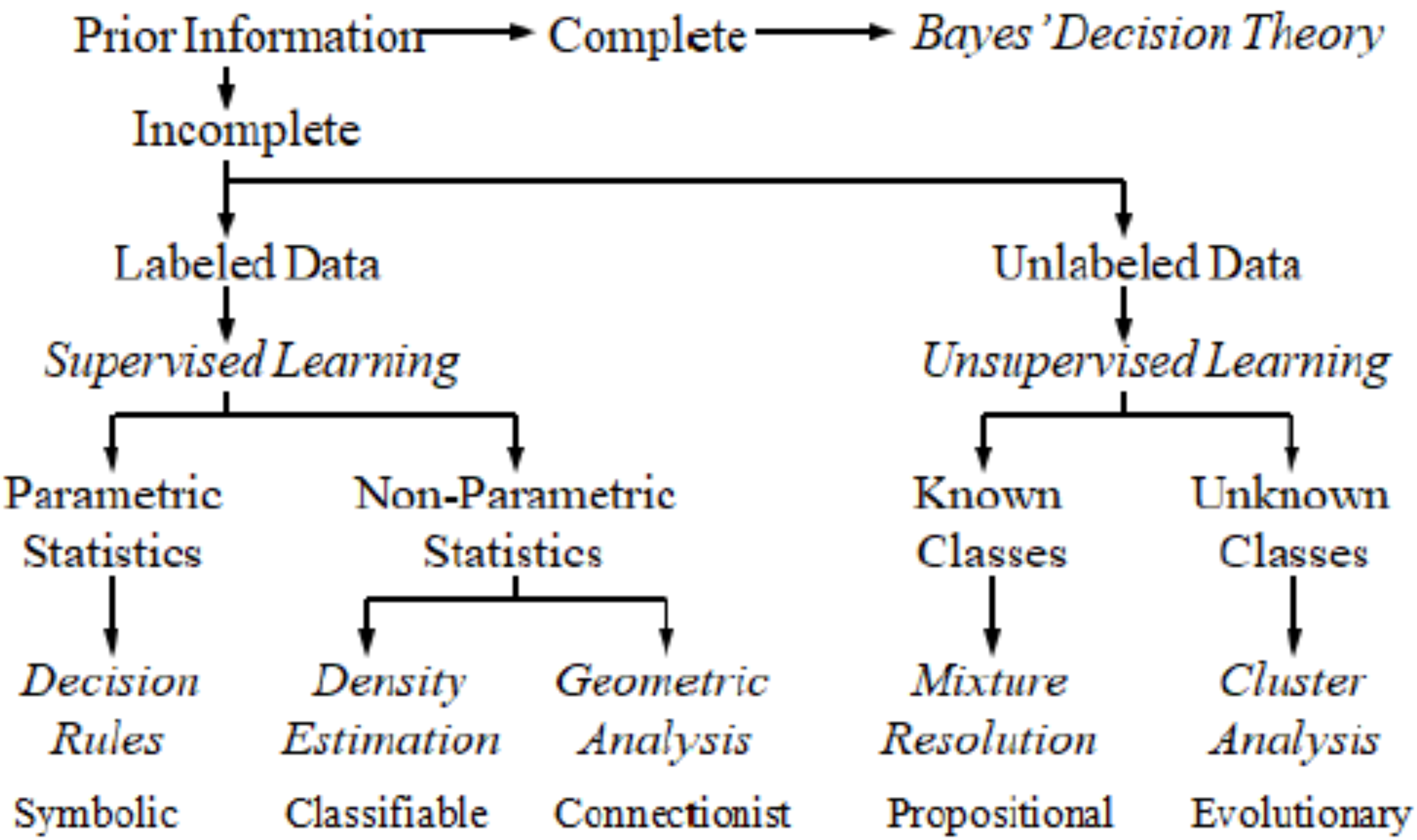
- Fusing of ***non-contemporaneous measurements***
- Reconfiguration of a single sensor in real-time by changing operating waveforms, modes, frequencies, or beamforming
- ***Need to define a sensor by its functions, not its physics***



World Models

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

Partitioning Of World Models Based On Amount Of Information *



* [Blasch *et al.*, 29]

Issues with World Models (kArpp)

- Observations of the real world **contain uncertainties**
  - **Aleatory**: Signals with additive measurement noise
    - Signals **can** have their uncertainty decreased by additional observations
  - **Epistemic**: Unmodeled or uncertainties in process model, e.g., process noise in K-filter, latent variables in Bayes Net
    - Signals **cannot** have their uncertainty decreased by additional measurements
    - Signals **can** have their uncertainty decreased by identifying the target and changing process model
- Differentiation between noise and clutter
  - **Noise**: random data added to signal (SNR), usually AWGN
  - **Clutter**: presence of real signals whose SCR cannot be reduced by an increase in effective radiated power (ERP)

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

- Bayesian nets (BN)
  - Directed acyclic graph (DAG) comprised of nodes and edges showing ***conditional probabilistic relationships***
  - Assigns probabilities to individual hypotheses
  - Causal and non-causal BN*
- 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
- If hypotheses are mutually exclusive, DS becomes equivalent to BN

* 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.

Benefits 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

Operational Issues in SM

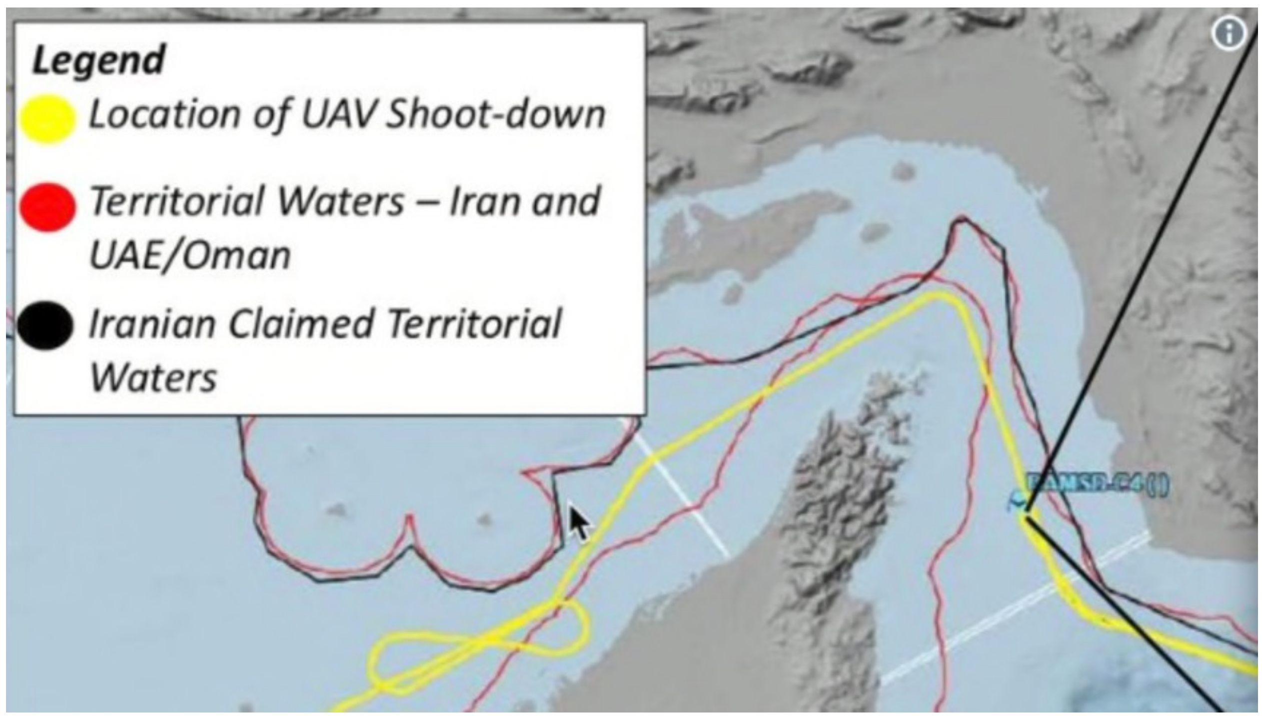
- Route Planning
- Redundant coverage
- Data fusion or decision fusion
- Centralized, distributed, or hybrid management
- Design considerations

Operational Issues in Sensor Management: Route Planning

PERQUIRE RESEARCH

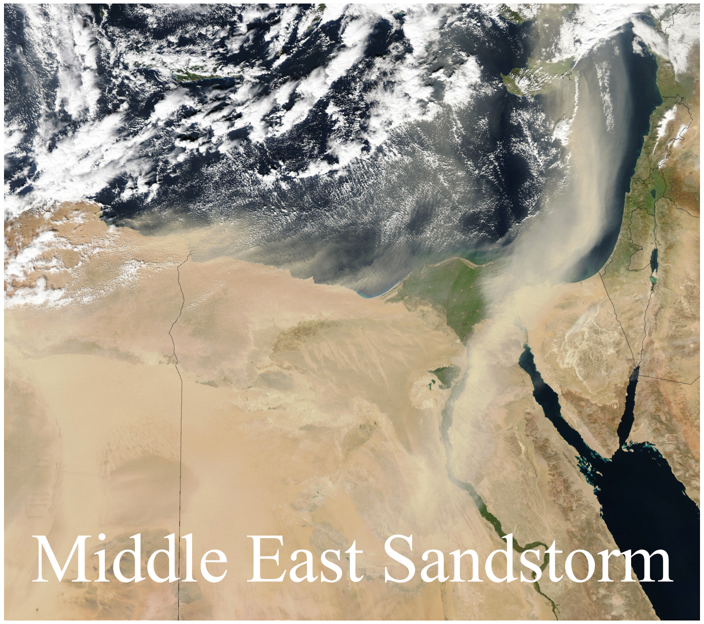
University at Buffalo
The State University of New York

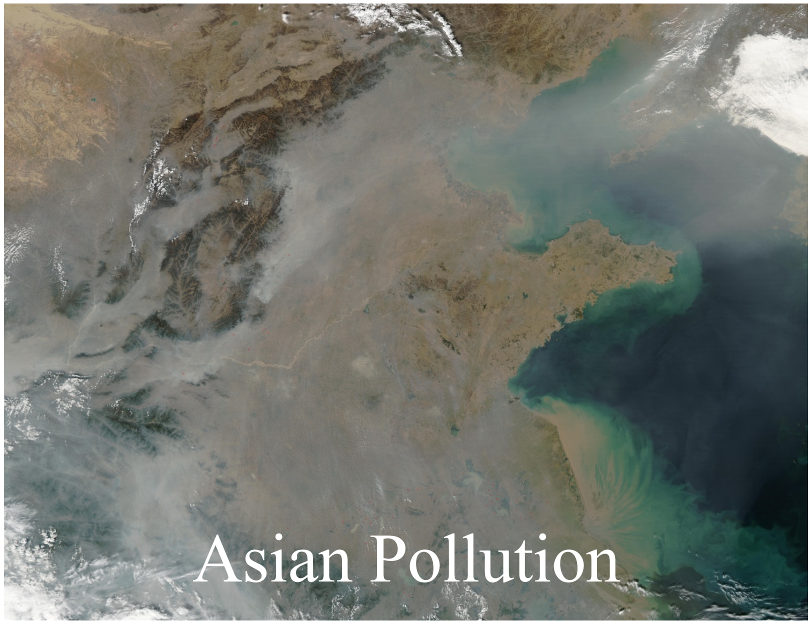
- Best accuracy
- Minimum shielding
- Best probability of observing
- Minimize jamming, clutter, spoofing
- Minimize probability of hostile action
- Communications links
- Maximize information
- Minimize fuel usage



Redundant Coverage

- 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





Data Fusion Issues

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

Hard and Soft Fusion of NonCommensurate Data Types

- 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?

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

PERQUIRE RESEARCH

University at Buffalo
The State University of New York

- 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

Soft Sensor Uncertainties: Bias & Observer Reliability

PERQUIRE RESEARCH

University at Buffalo
The State University of New York

- 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

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)

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)

$$WAM = \sum w_i d_i$$

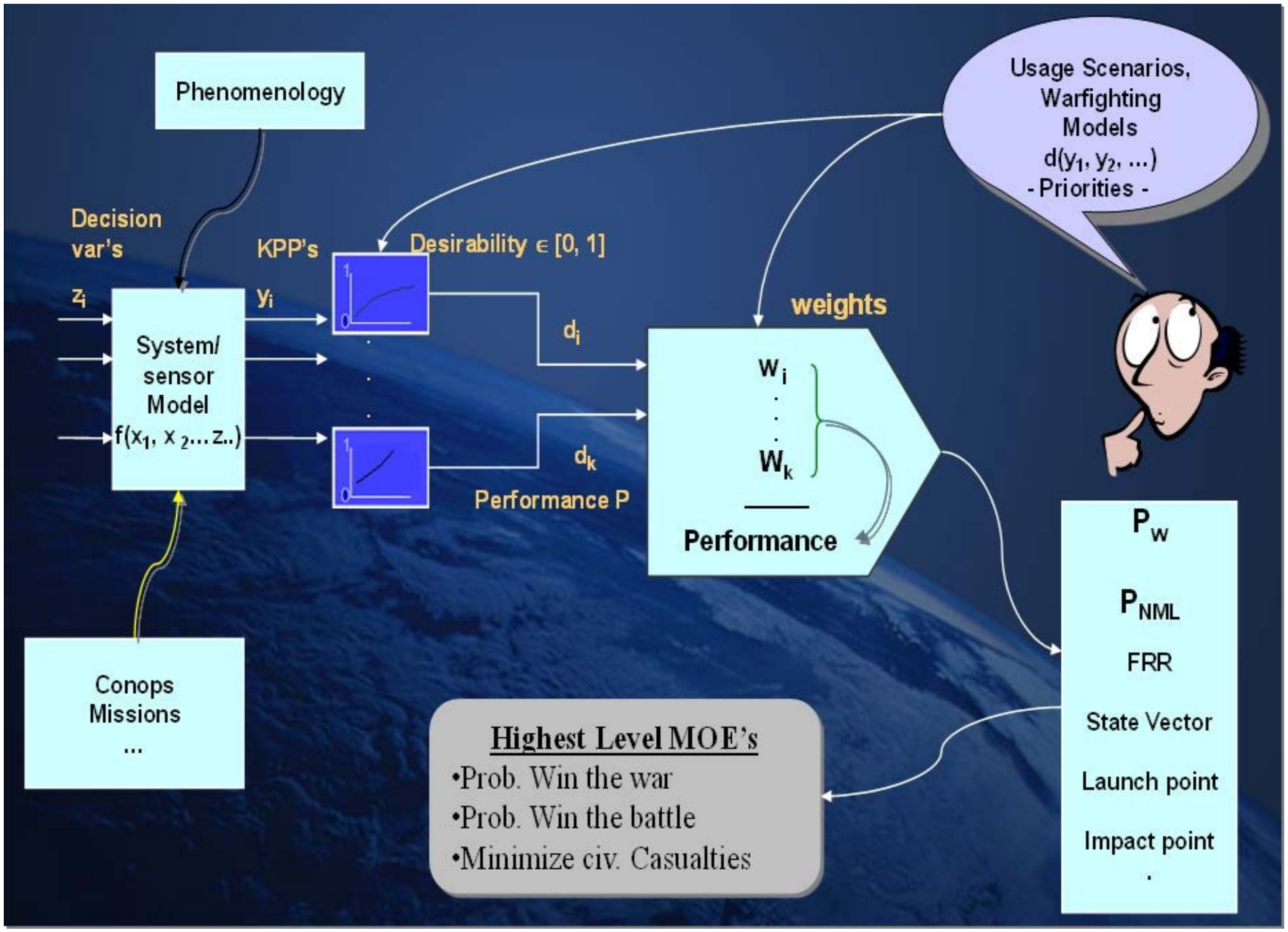
where d_i is a desirability measure

where w_i is a weight assigned to that measure

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***

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?

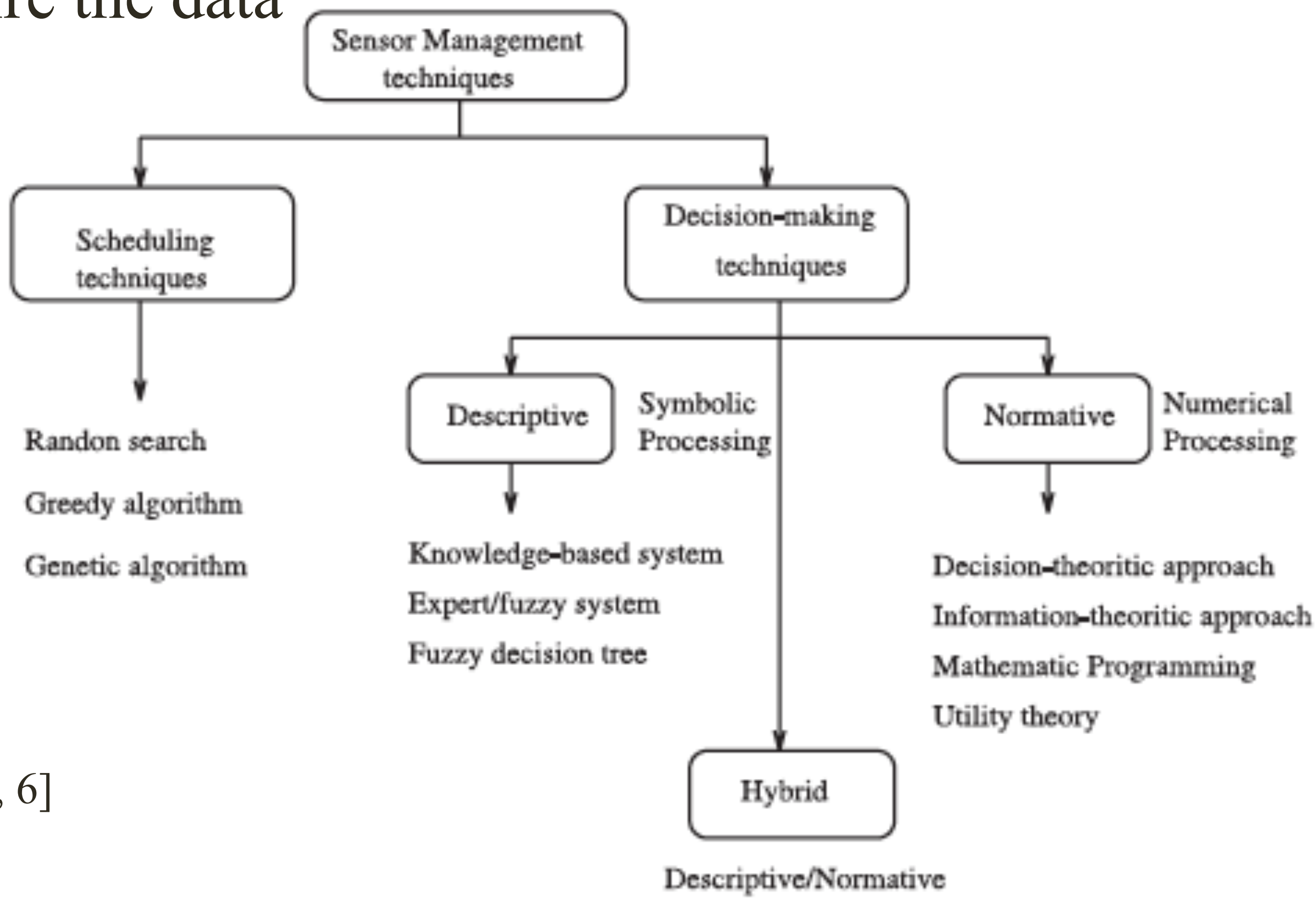
- The ***globally optimal*** (infinite time horizon) sensor management solution is ***not computationally feasible in real time*** and is a difficult combinatorial optimization problem
- It has been shown that the optimal sensor management policy can be found by ***linear programming***, but it is ***computationally intractable*** in real time.
- Dynamic programming has been used to effect in ***farsighted sensor*** management applied to a system for move/stop tracking
- 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

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
- “…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

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

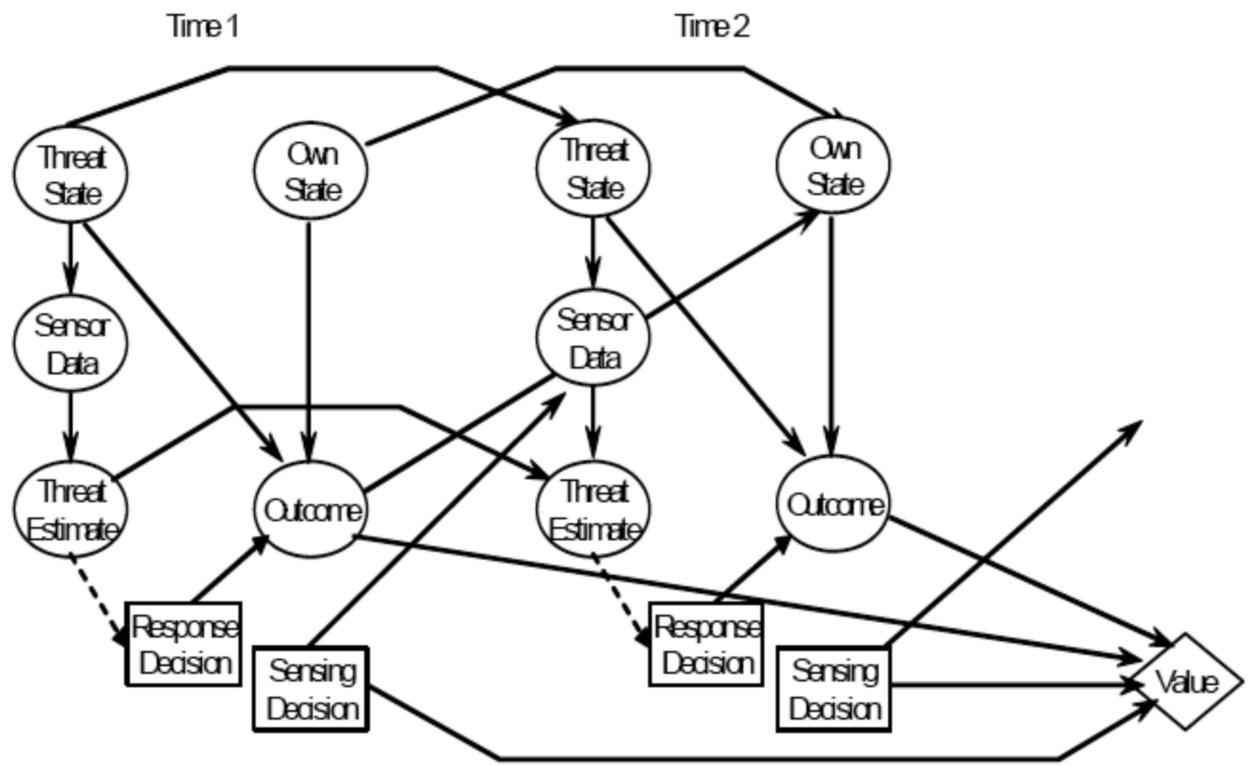
Normative Decision Based on EIVR

Expected information value rate (EIVR) is a useful measure for deciding the best next collection opportunity (BNCO)

- Two orthogonal myopic performance indices differentiate between ***situation information*** and ***sensor information***
  - Expected (***situation***) information value rate, $EIVR_{sit}$
    - Used to decide what information to obtain
  - Expected (***sensor***) information value rate, $EIVR_{sen}$
    - Used to decide which sensor to use to acquire that informatiion
- Bayes Net provides a 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]

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.

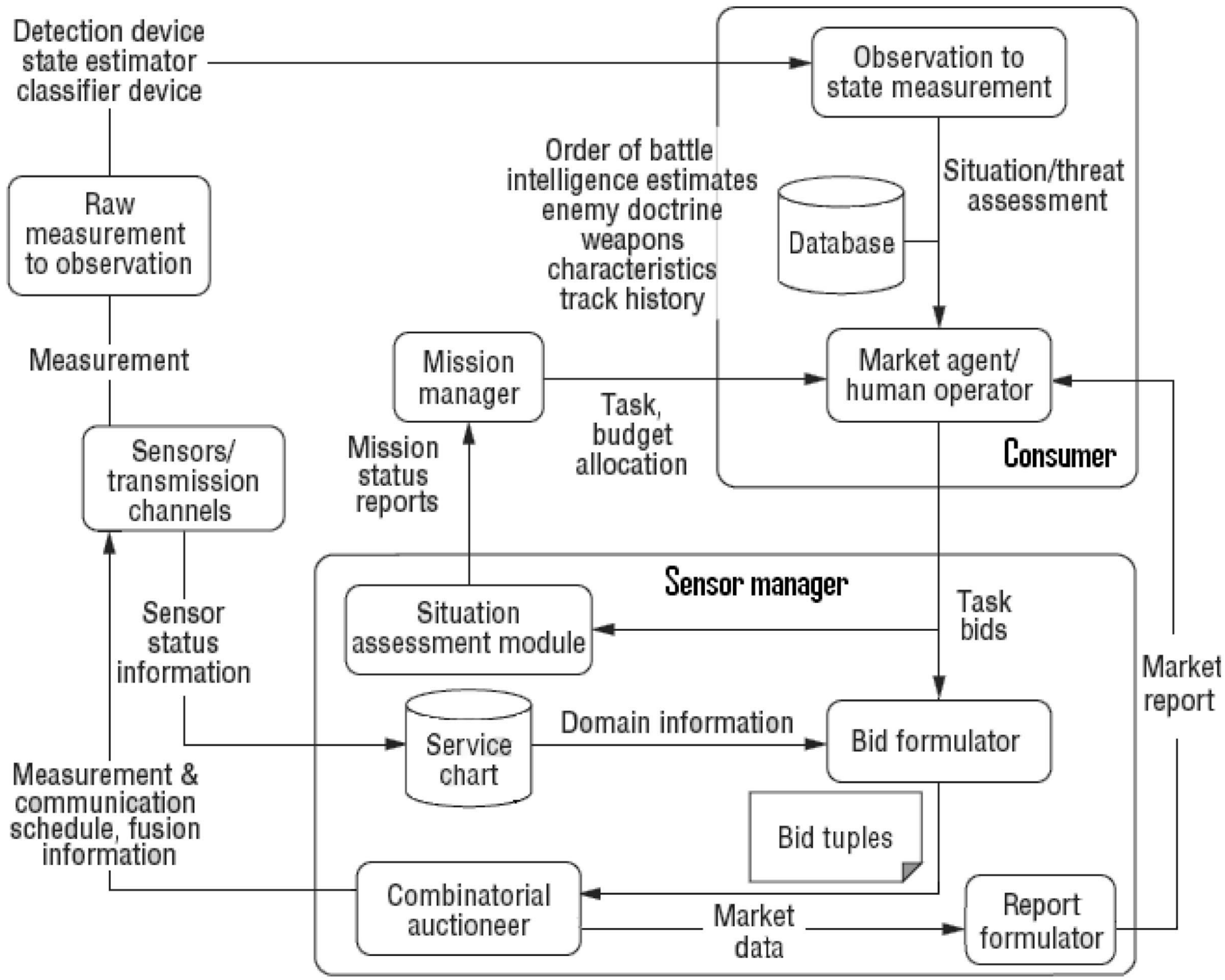
Game Theory

- 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 Based Decision Making

- "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]
- 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
- 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]

Sensor Management Architectures

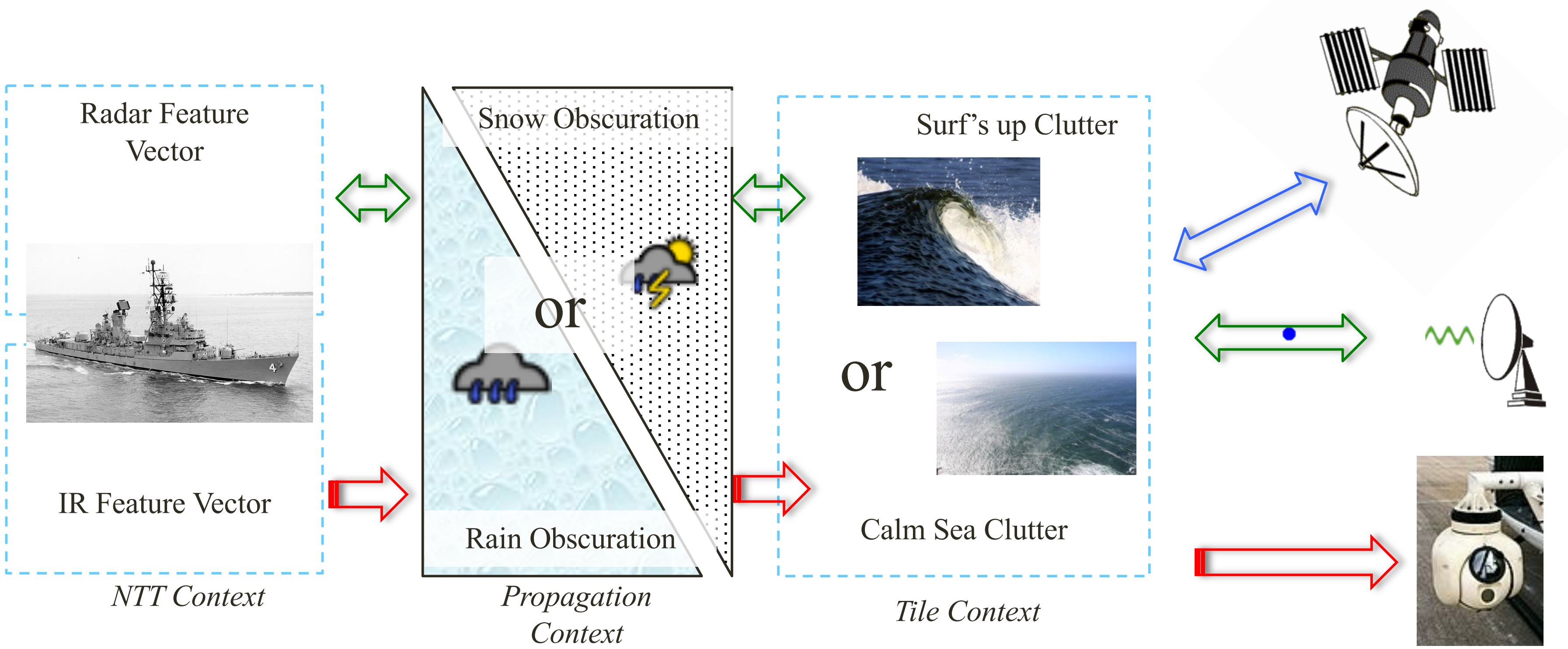
- Centralized
  - Most industrial sensor systems have a regular, non-time varying structure amenable to centralized control
  - SCADA
  - Difficulty with centralized control is tendency to micromanage
- Distributed or decentralized
- Hierarchical
- Hybrid of centralized and decentralized

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

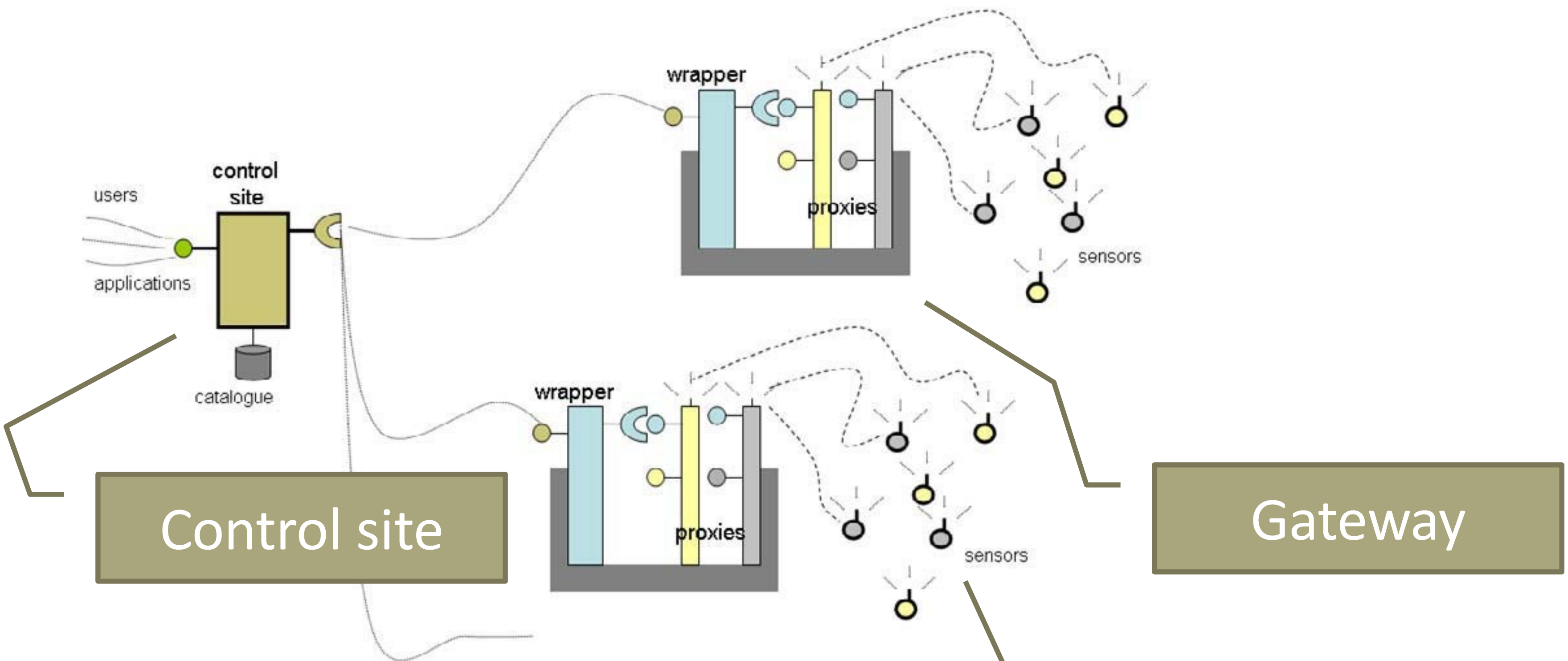
Hybrid Approach

- 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.



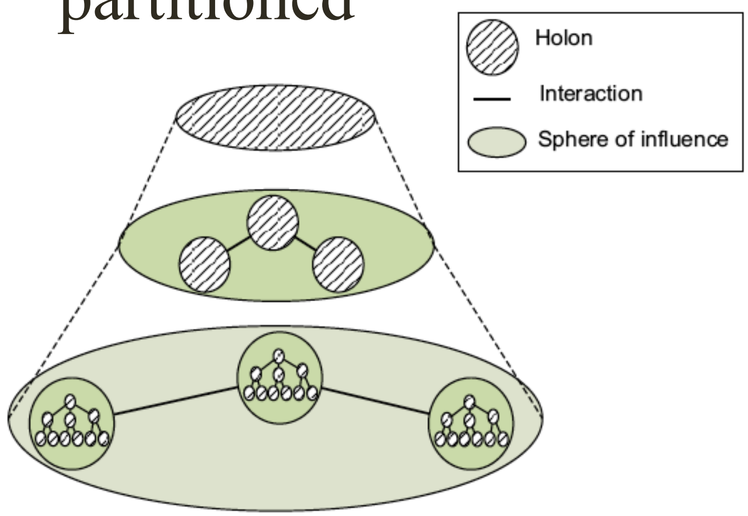
L. Gurgen, C. Labbe, V. Olive and C. Roncancio, "A Scalable Architecture for Heterogeneous Sensor Management," in 16th International Workshop on Database and Expert Systems Applications (DEXA'05), Copenhagen, 2005.

PERQUIRE RESEARCH

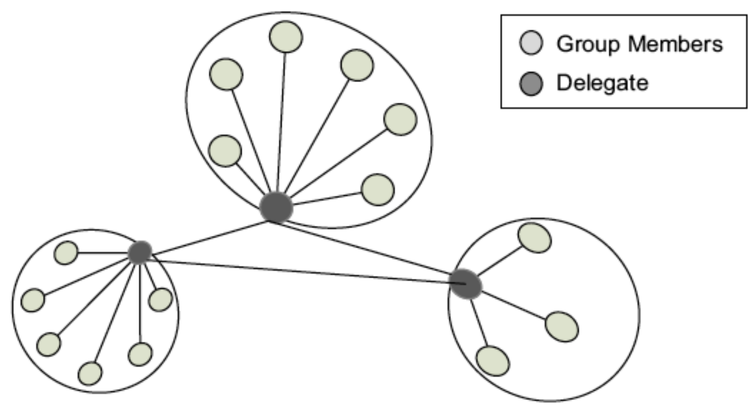
University at Buffalo
The State University of New York

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



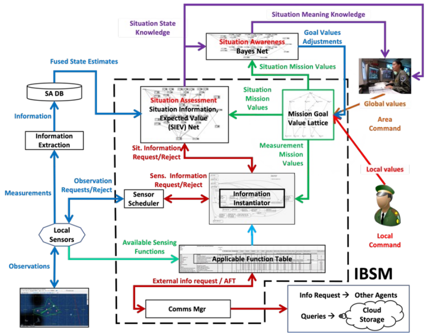
(b) Federation architecture

* [Hilal *et al*., 32]

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



Information Based Sensor Management (IBSM)

Ken Hintz

ken.hintz@perquire.com
Associate Professor, Mechanical and Aerospace Engineering
U. of Buffalo
Associate Professor Emeritus, Electrical and Computer Engineering,
George Mason University

Outline of IBSM Presentation

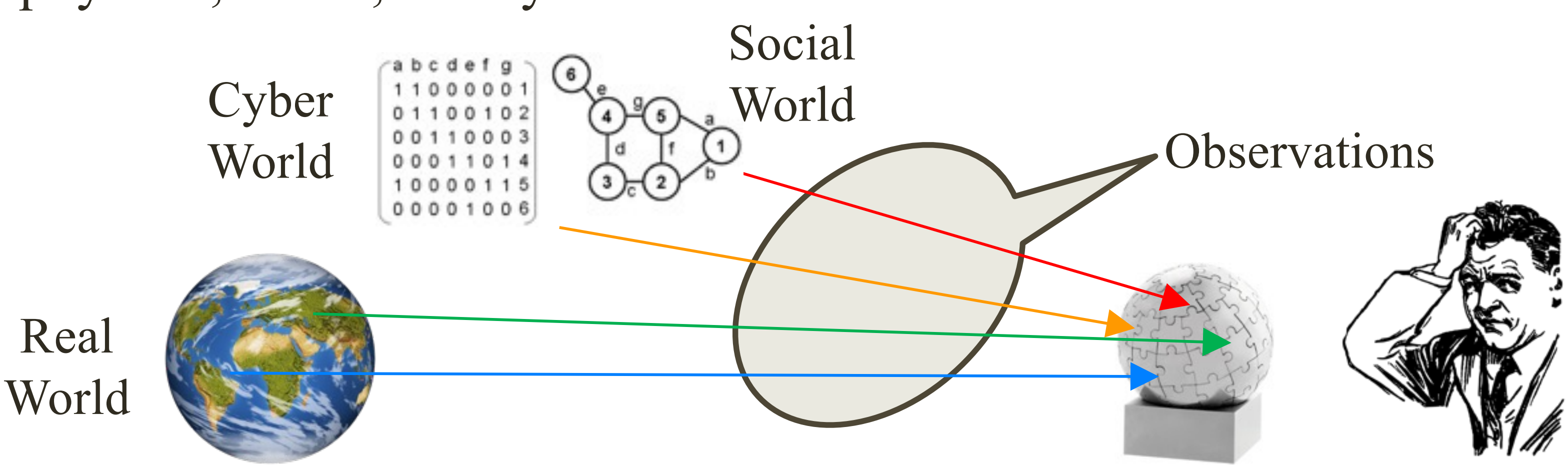
- ***Motivation*** for information based sensor management (IBSM)
- Underlying principle is ***maximizing expected information value rate***, *EIVR,* from the real world to the mathematical model of the world
- ***Situation*** information *vs* ***sensor*** information
- ***Functional decomposition***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

Requirement and Constraints

- 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 already 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***

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

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 as measured in bits

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

- 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 aleatory nodes in the BN. Formally, the knowledge entropy of a BN, *KEn,* is

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

- 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***

PERQUIRE RESEARCH
University at Buffalo
The State University of New York

IBSM Provides Accurate, Timely, Valued Information For Decision Makers

- ***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

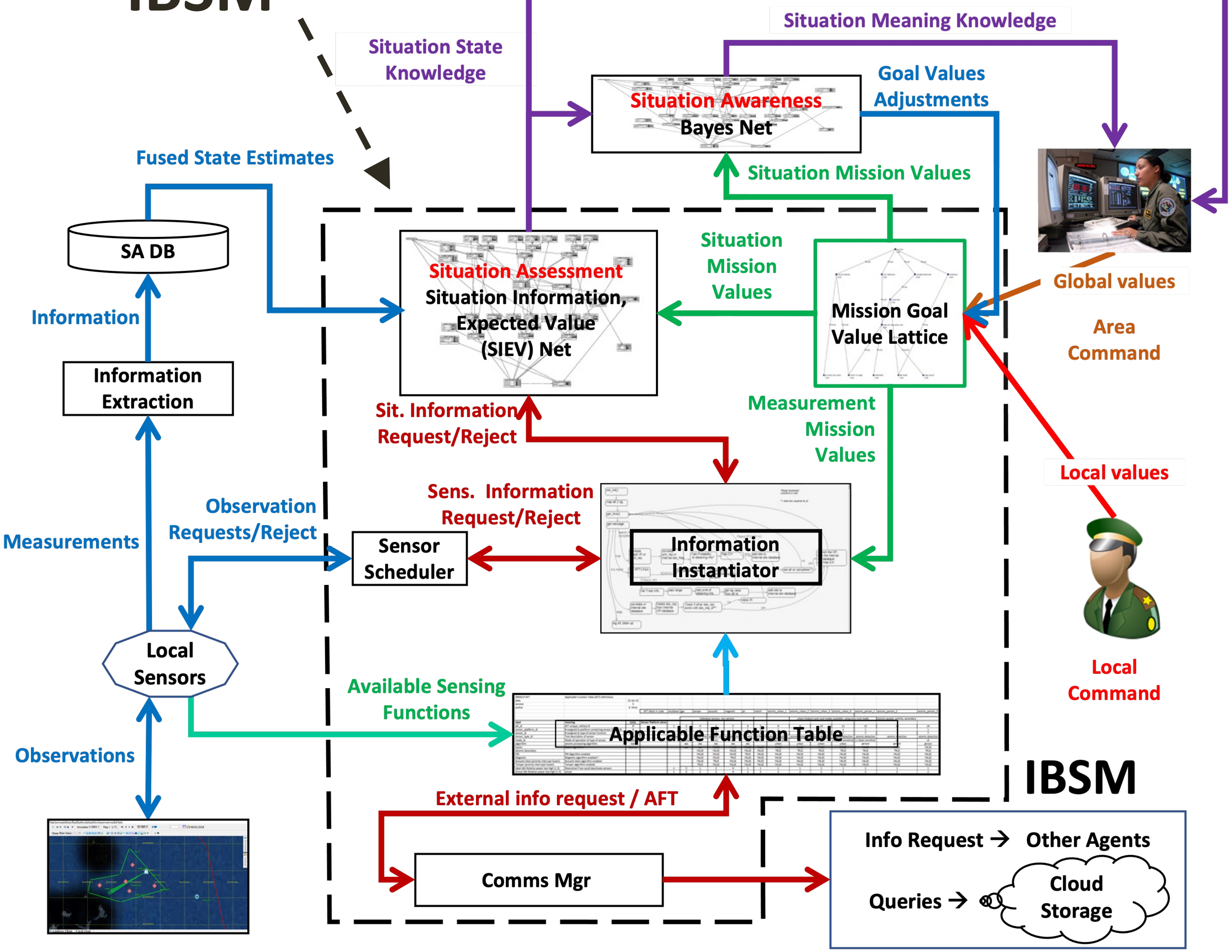
Implementation of IBSM

- 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

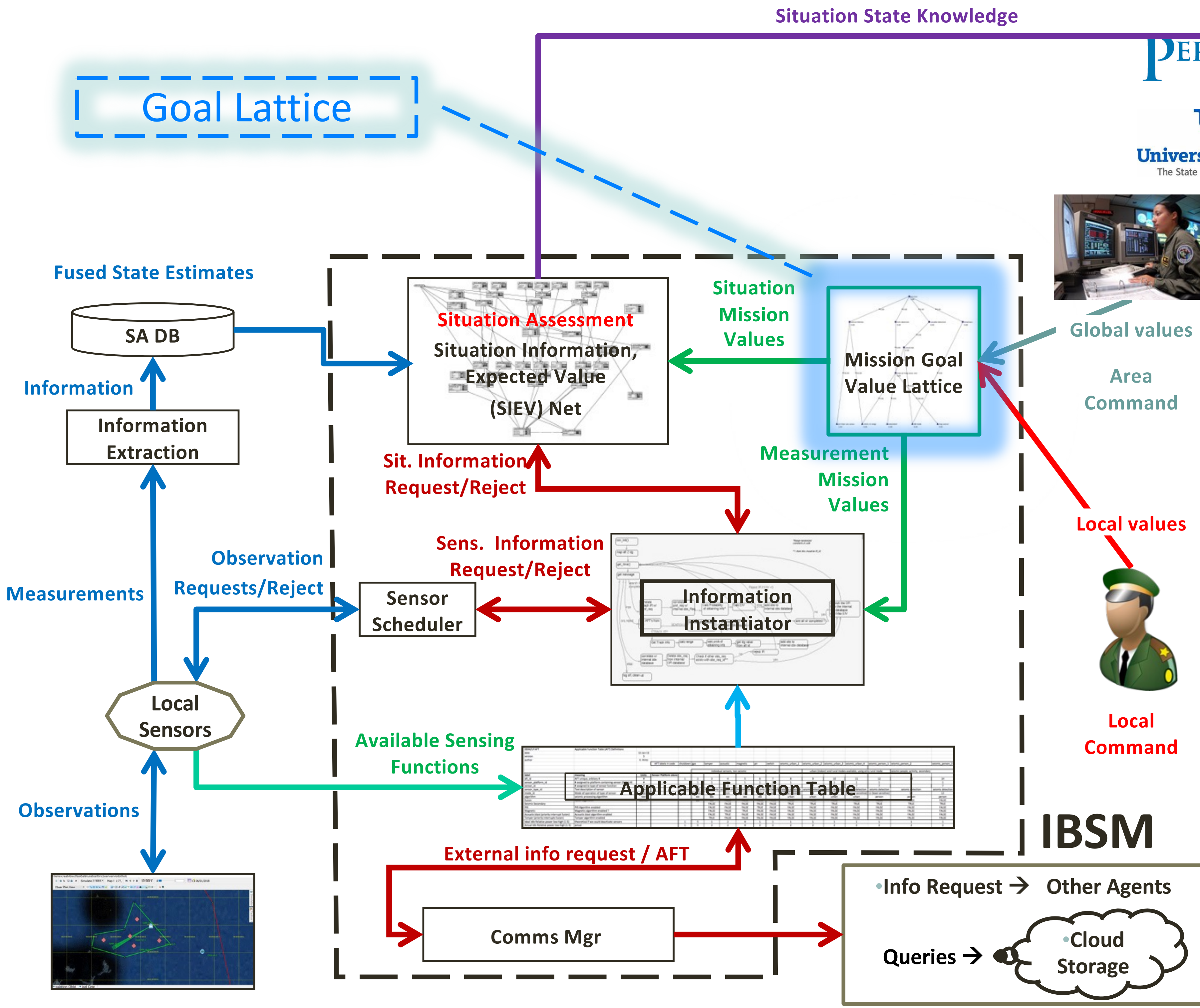
1. ***Goal lattice (GL)*** assigns mission values to situation information needs and sensor observations
2. ***Situation Information Expected Value Network (SIEV-net)*** maintains situation assessment in Bayes Net
3. ***Information Instantiator (II)*** maps situation information needs to sensor functions
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



Perquire Research

University at Buffalo
The State University of New York


Situation State Knowledge
Goal Lattice
Perquire Research
University at Buffalo
The State University of New York
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
Sit. Information Request/Reject
Measurement Mission Values
Local values
Sens. Information Request/Reject
Sensor Scheduler
Information Instantiator
Local Command
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***

Goal Lattice Apportions Mission Value Among Sensor Actions

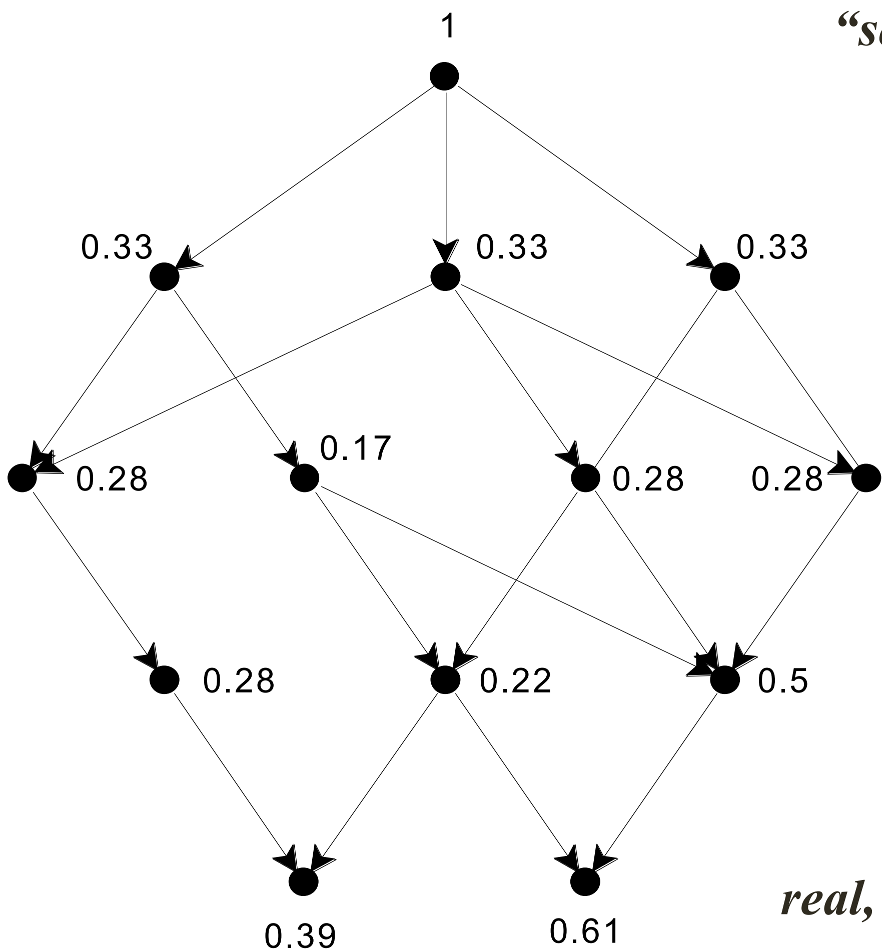
PERQUIRE RESEARCH

University at Buffalo
The State University of New York

- 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

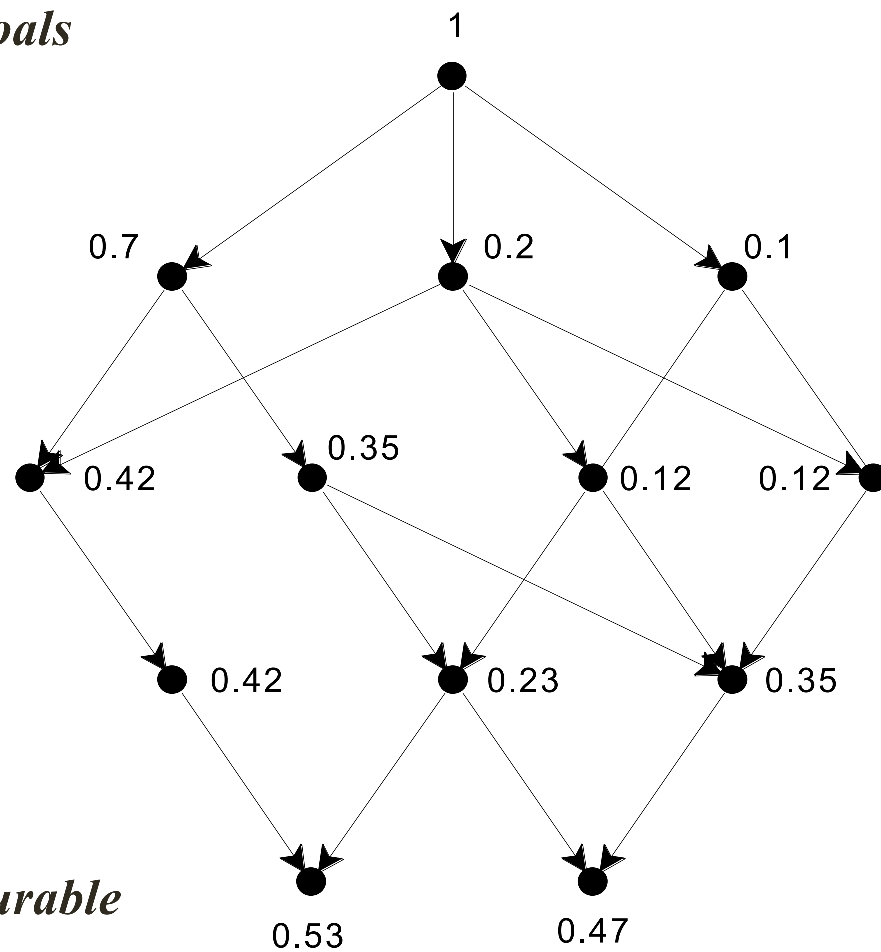
Uniform Apportionment



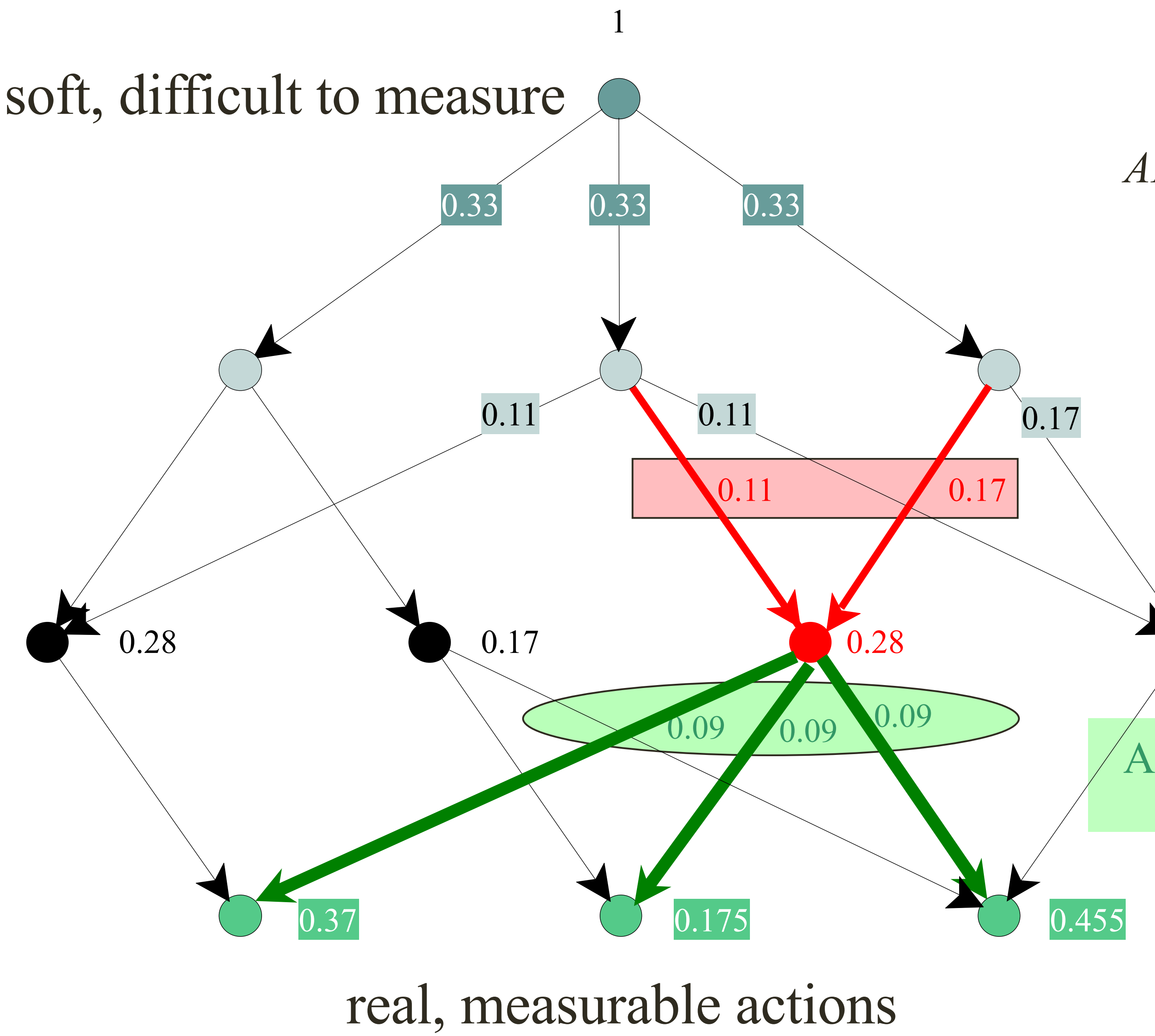
"soft" goals

real, measurable information requests

User Preference



Goal Lattice Numerical Example



e.g., EQUAL APPORTIONMENT

ACCRUAL
(from higher)

APPORTIONMENT
(among lower)

Mission-Based GL Example

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

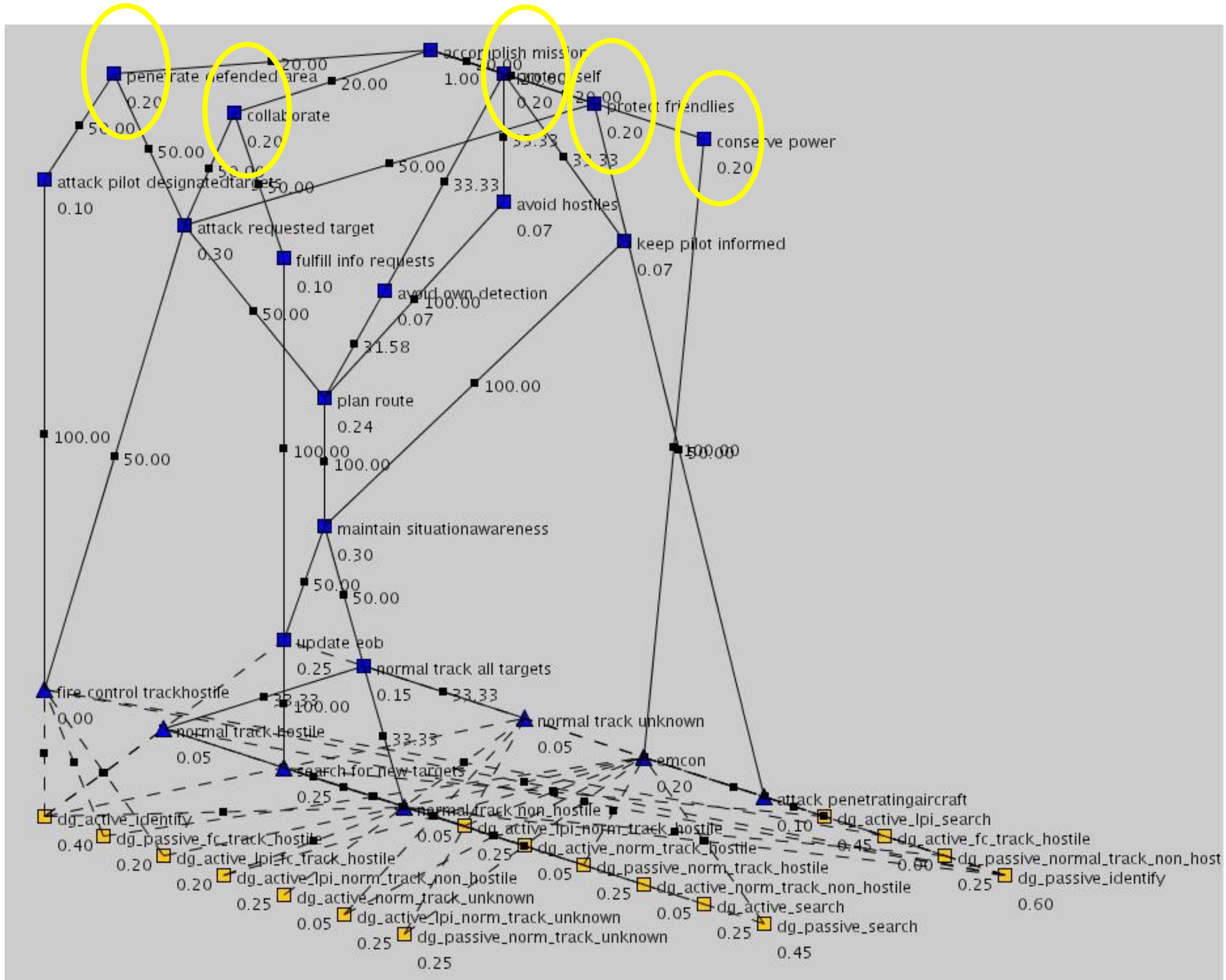
Protect Self

Protect Friendlies

Conserve Power

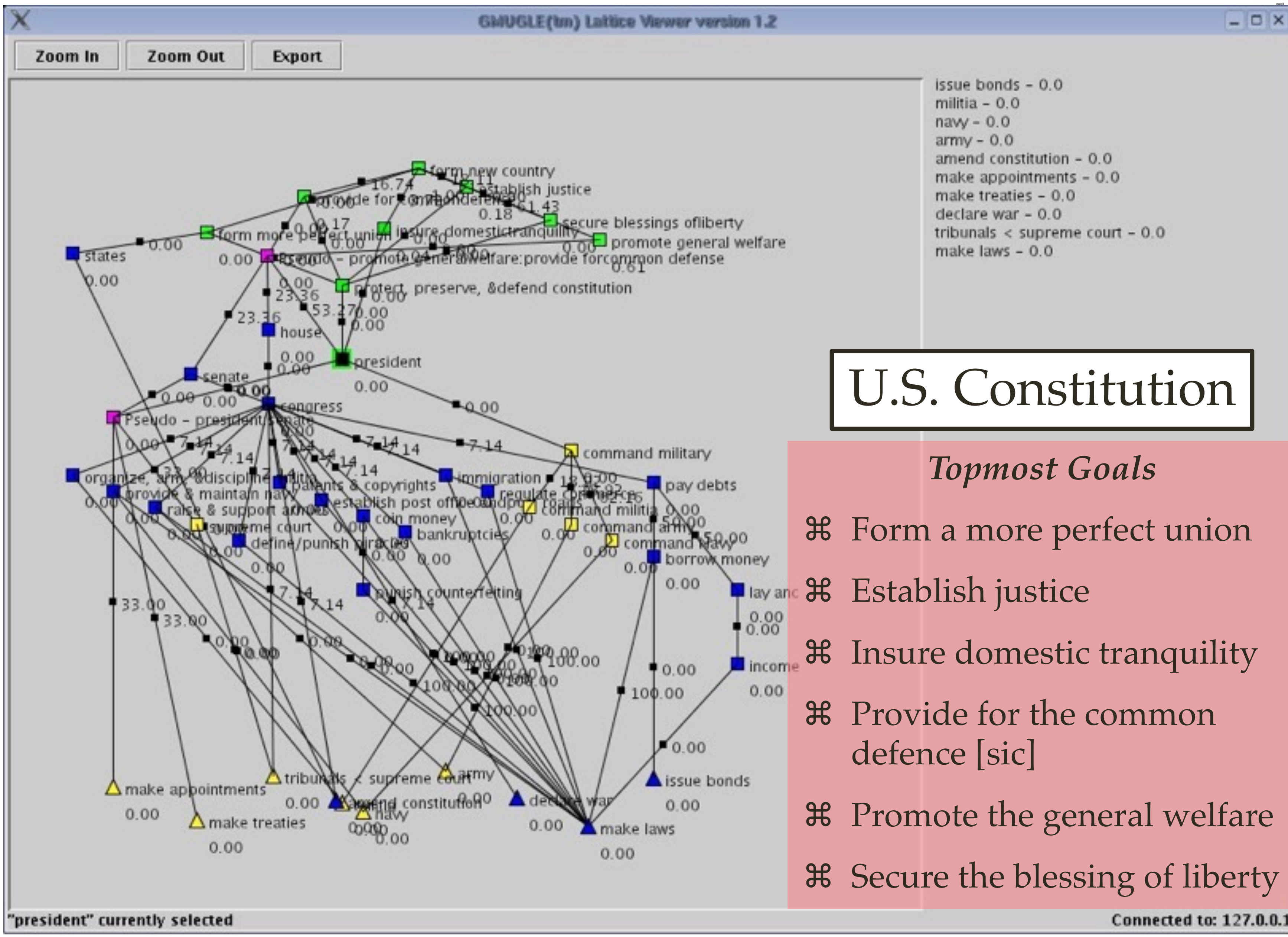
Penetrate Defended Area

Collaborate



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

US Constitution Example GL



U.S. Constitution

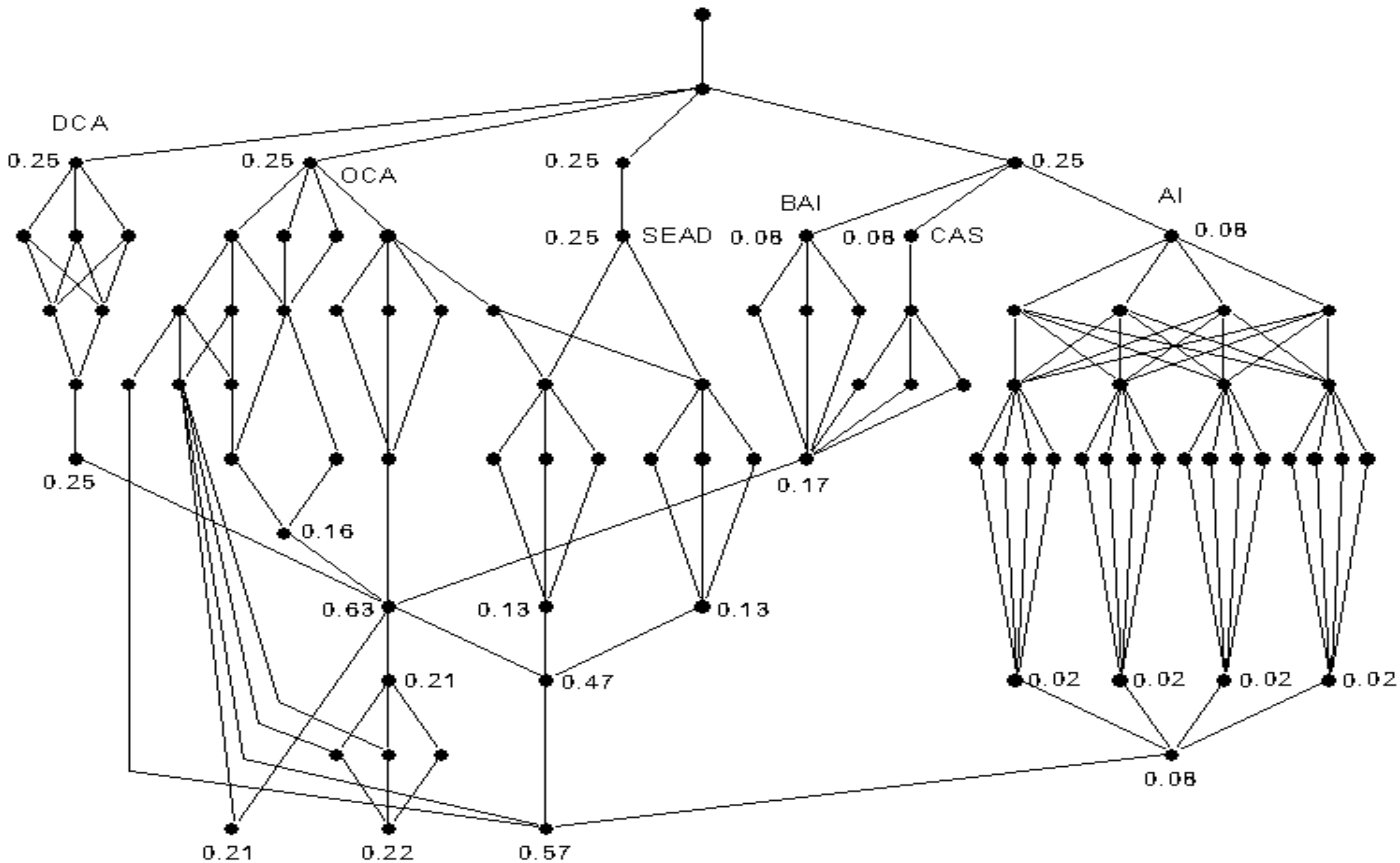
Topmost Goals

- ⌘ 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

PERQUIRE RESEARCH

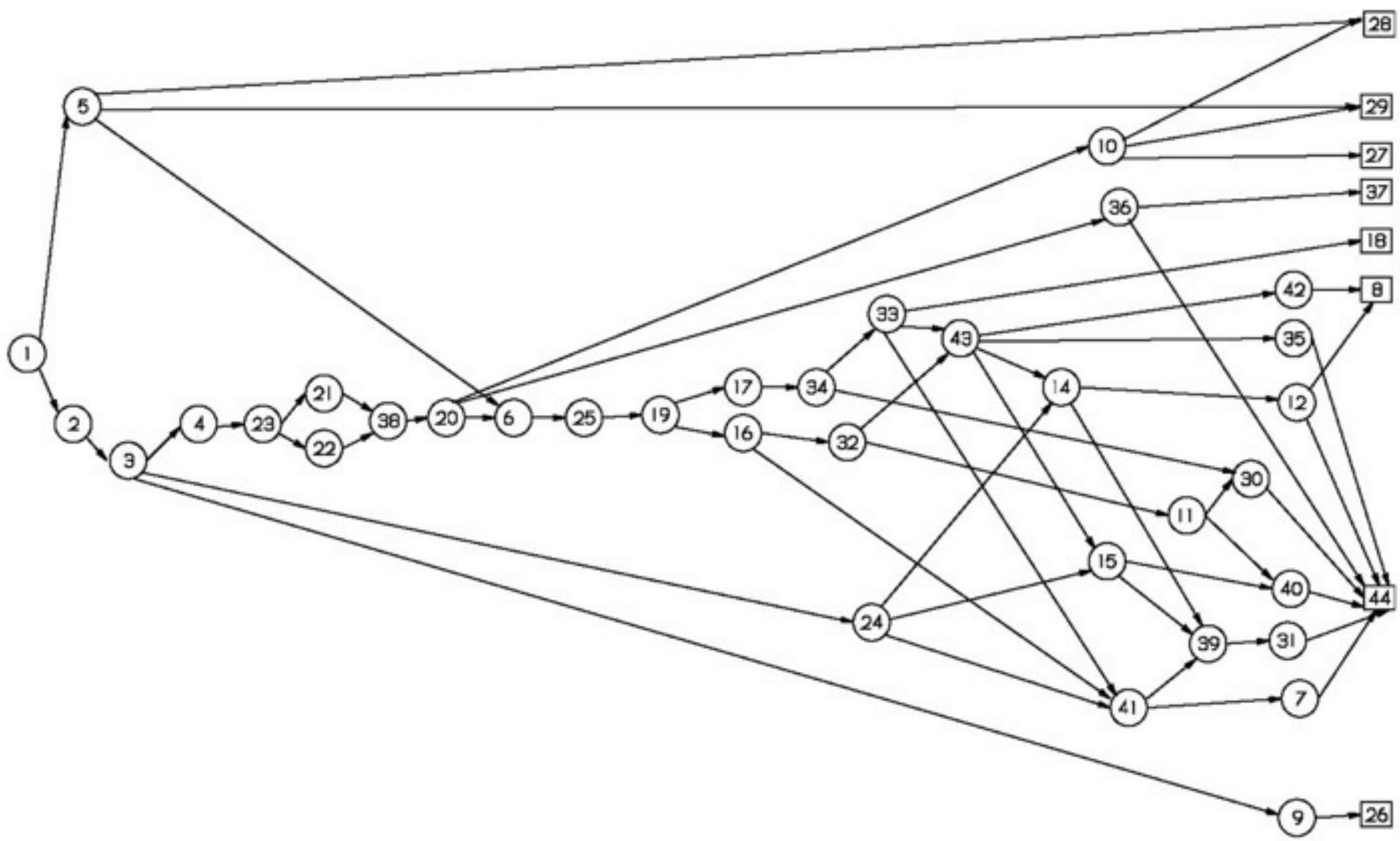
University at Buffalo
The State University of New York



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

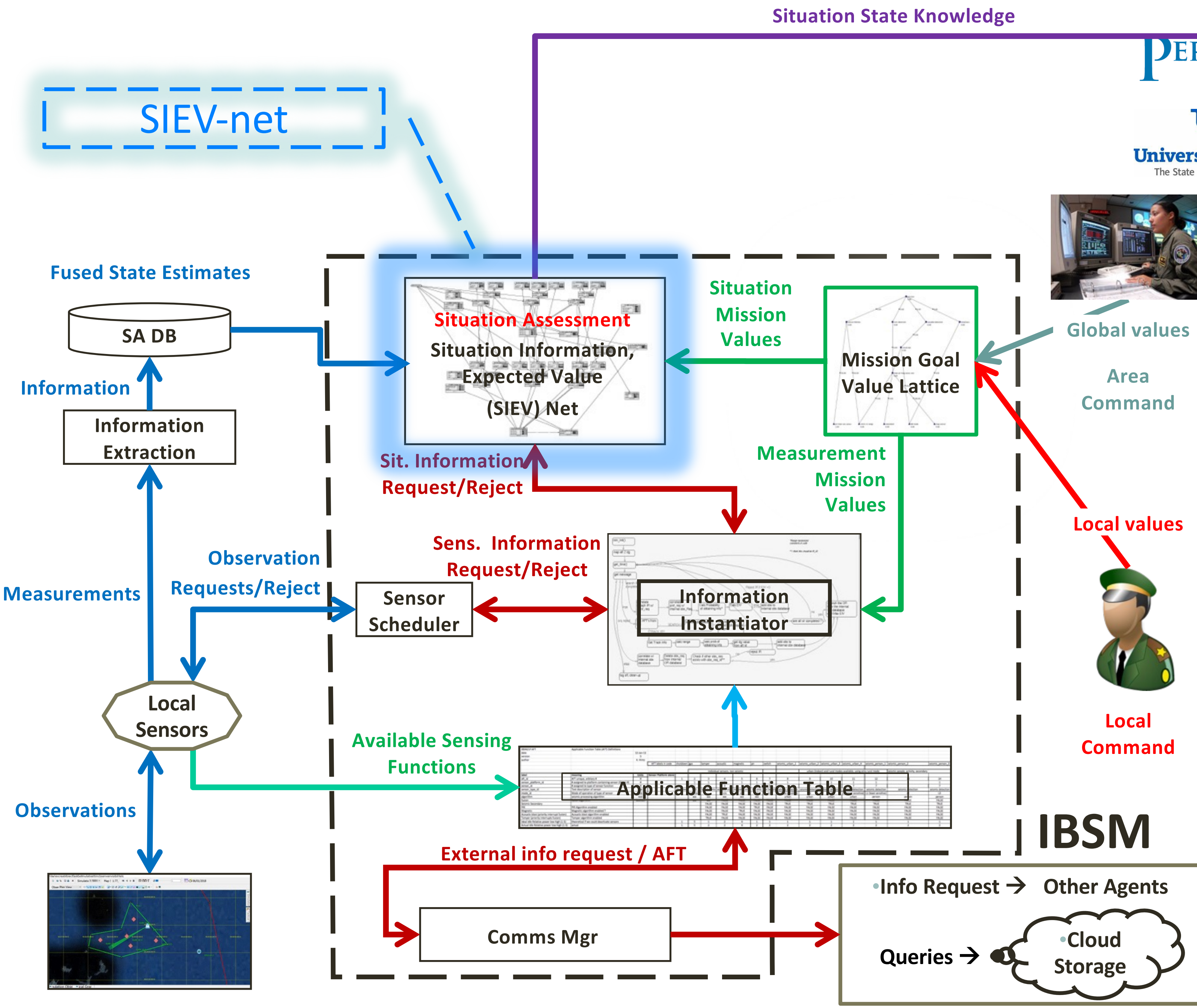


Goal Lattice Creation

- 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)


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

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

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***

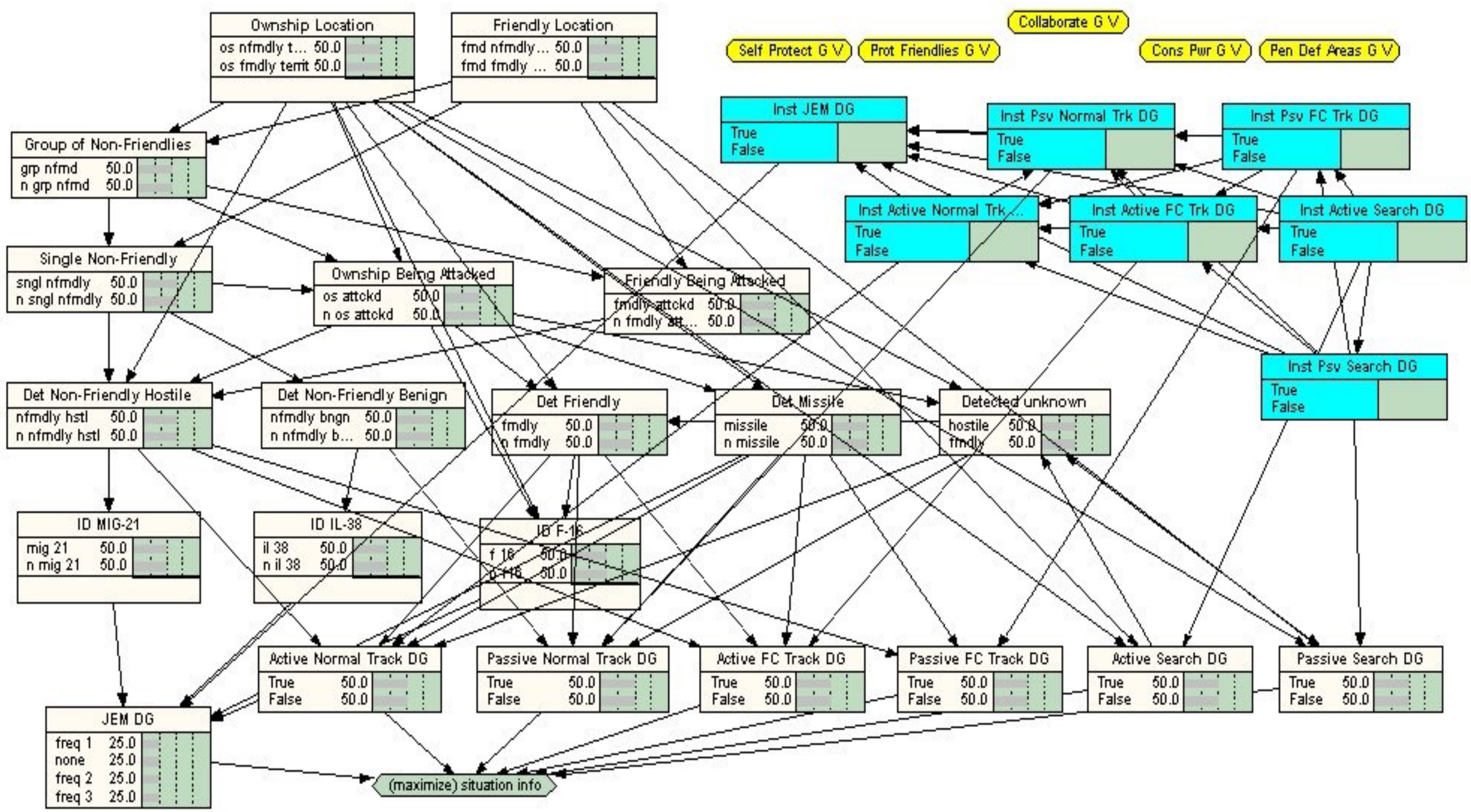
Need for Information Measure

- 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 ($\boldsymbol{EIVR_{sit}}$)
- 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

Example SIEV-net



Partitioned SIEV-Net Showing Managed Evidence Nodes (Sensors)

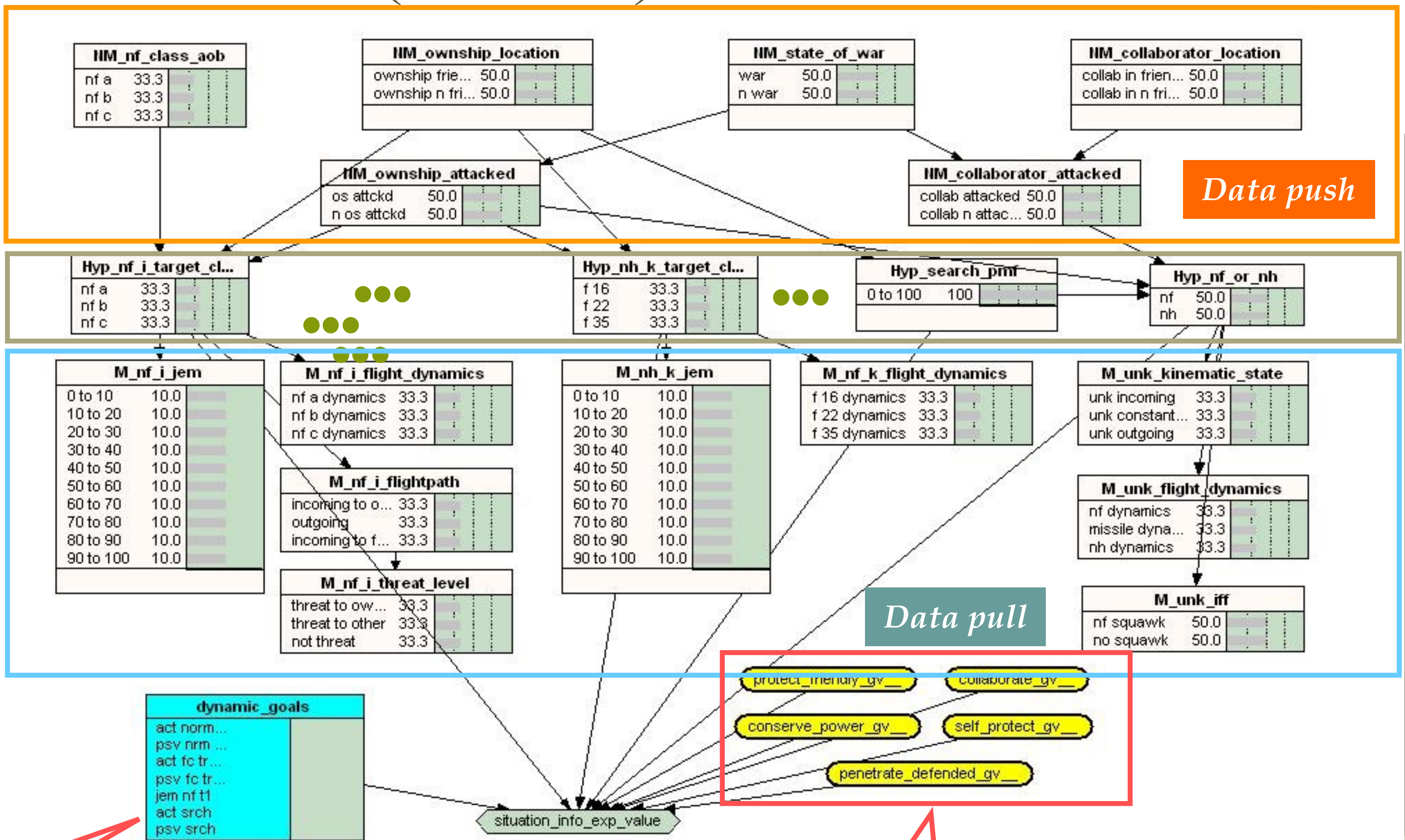
PERQUIRE RESEARCH

University at Buffalo
The State University of New York

Non-managed evidence nodes

Situation chance nodes

Managed evidence nodes



Decision node

Utility node

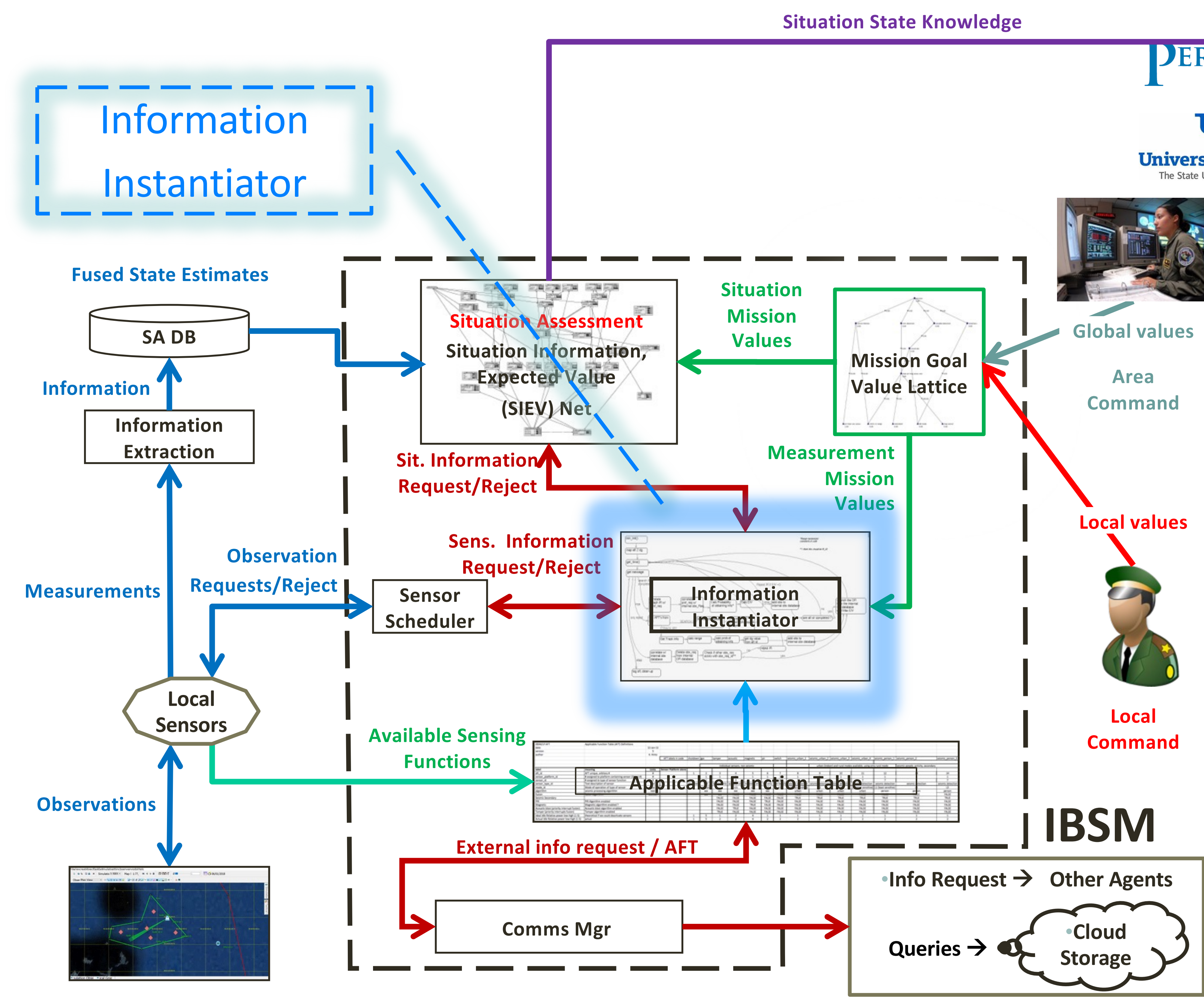
Topmost goal values from GL

Usage of the SIEV-Net

Perquire Research

University at Buffalo
The State University of New York

- $EI_{sit}VR$ 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



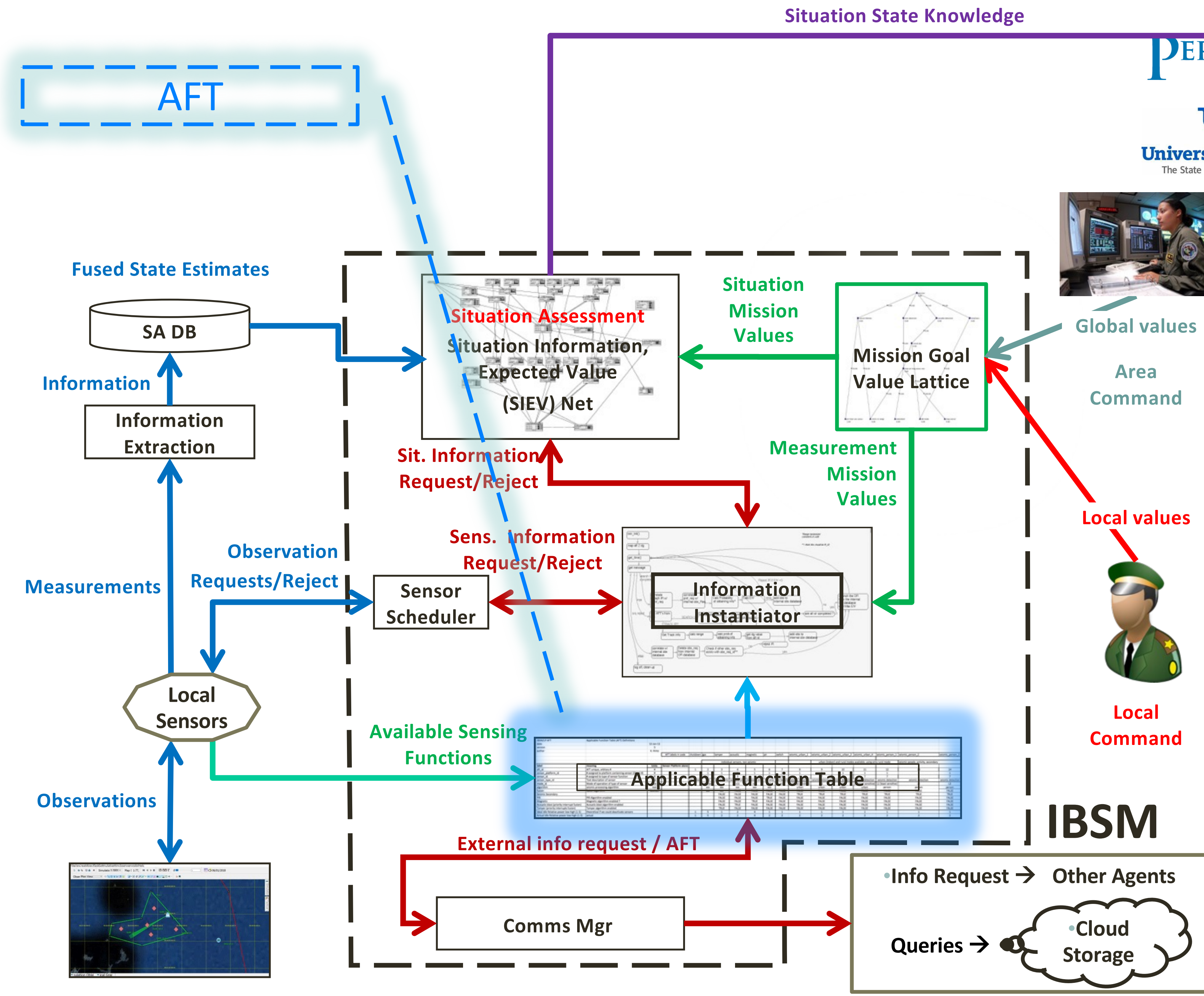
Information Instantiator
Situation State Knowledge
Fused State Estimates
SA DB
Information
Information Extraction
Measurements
Observation Requests/Reject
Local Sensors
Observations
Situation Assessment
Situation Information, Expected Value
(SIEV) Net
Situation Mission Values
Mission Goal Value Lattice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

IBSM Component: (Situation) Information Instantiator

- 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



Situation State Knowledge
AFT
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
Sit. Information Request/Reject
Measurement Mission Values
Local values
Sens. Information Request/Reject
Sensor Scheduler
Information Instantiator
Local Command
Available Sensing Functions
Applicable Function Table
IBSM
External info request / AFT
Comms Mgr
•Info Request → Other Agents
Queries →
•Cloud Storage
PERQUIRE RESEARCH
UB University at Buffalo The State University of New York

IBSM Component: Applicable (Sensor) Function Table

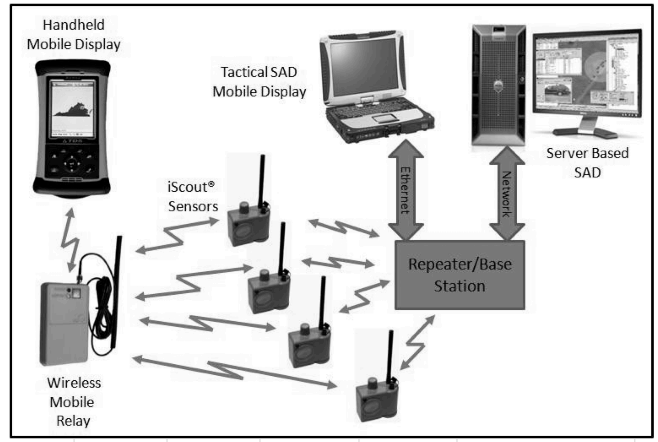
- Sensors have capabilities which are defined by their sensing functions
- Some sensor functions can be accomplished by multiple sensors each of which has ***different operational parameters*** resulting in ***different*** $\boldsymbol{EI_{sen}VR}$
  - A sensor may be capable of performing more than 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

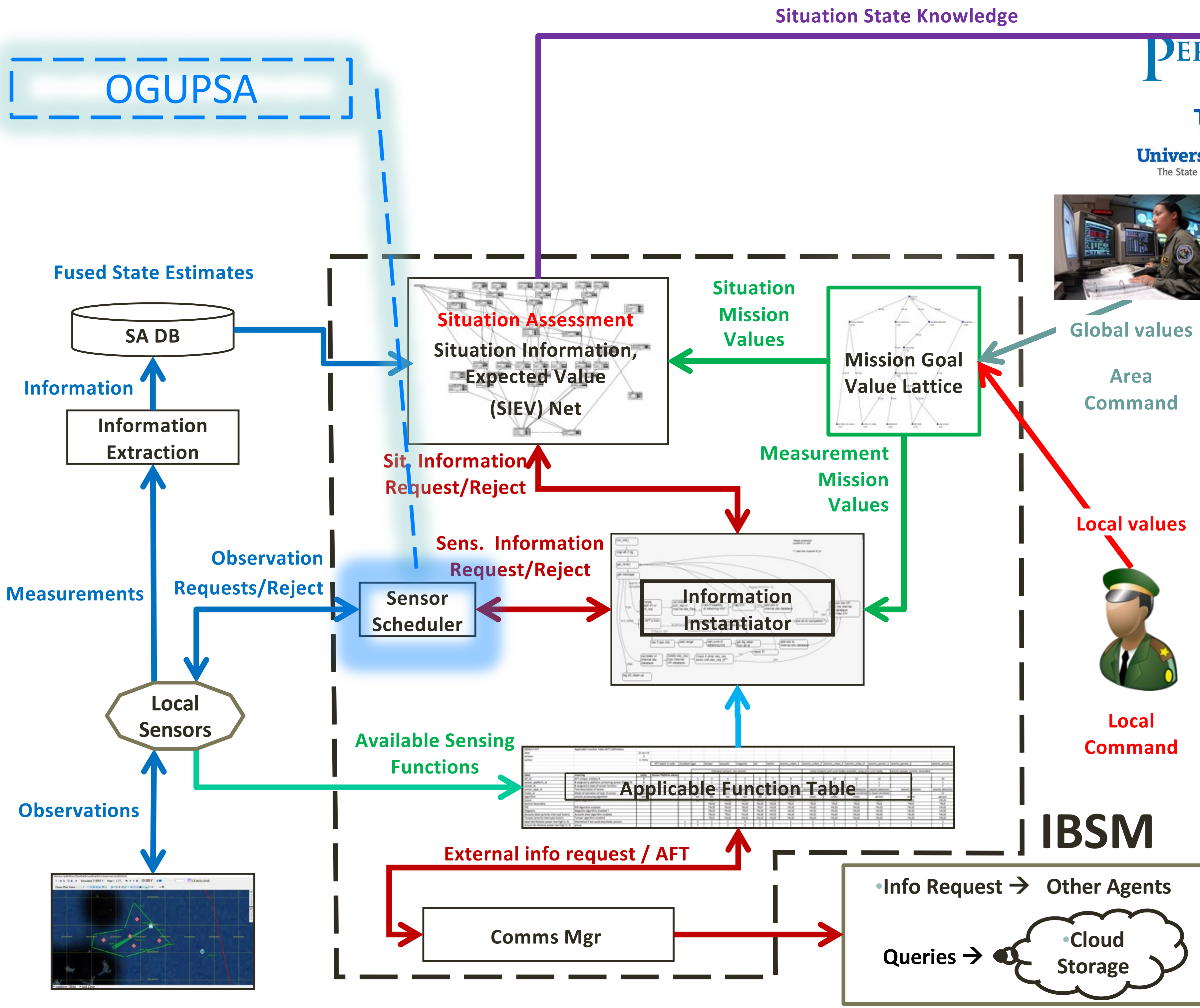
- Each sensor is required to have its AFT entry described in ***sensor modeling language*** (SML) which ***facilitates the use of new sensors***
- When a sensor is ***brought on-line***, it communicates its AFT functions to IBSM which uses it to populate AFT database
  - Includes operational parameters, 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

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

PERQUIRE RESEARCH
University at Buffalo
The State University of New York



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



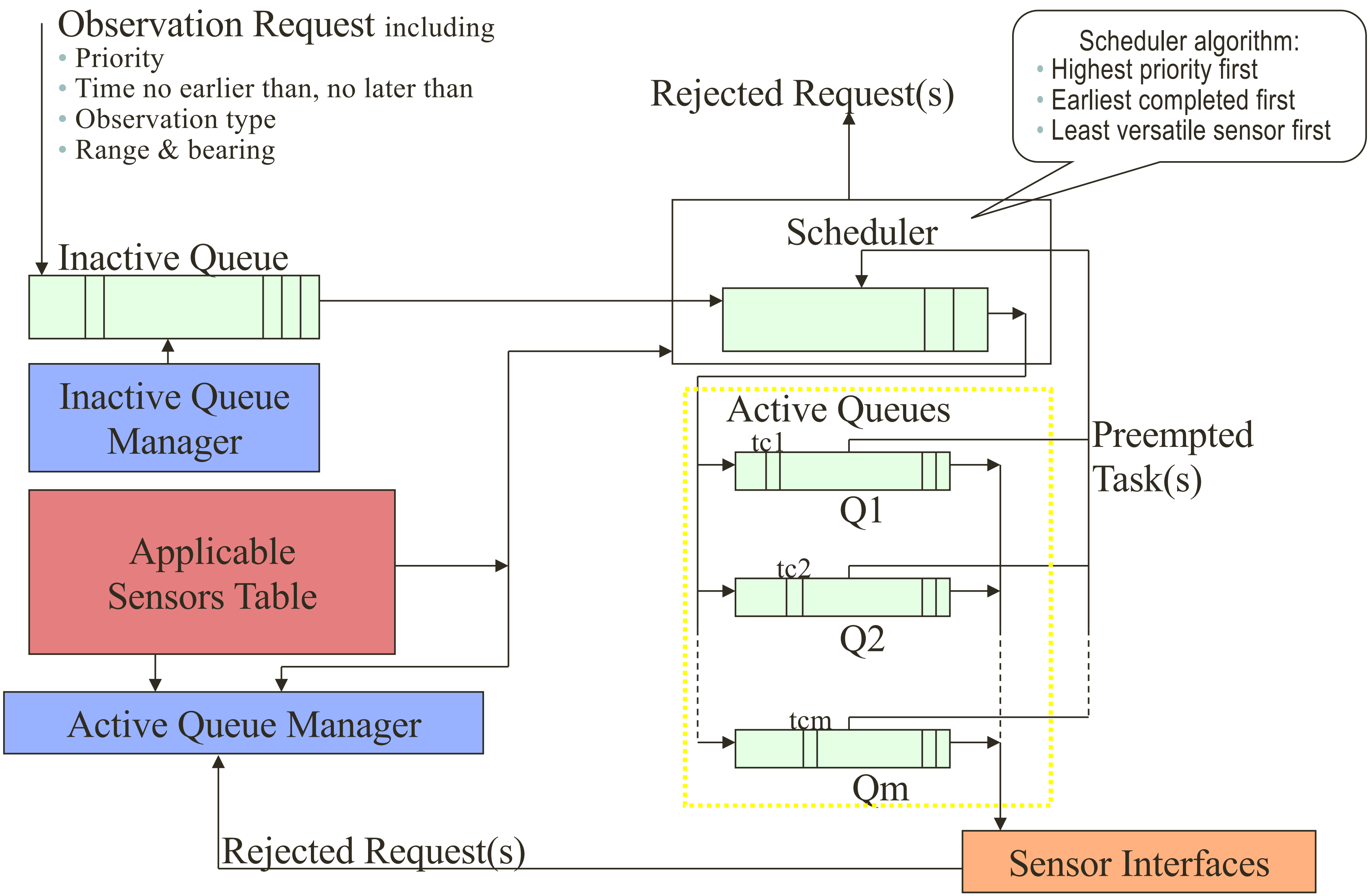
PERQUIRE RESEARCH

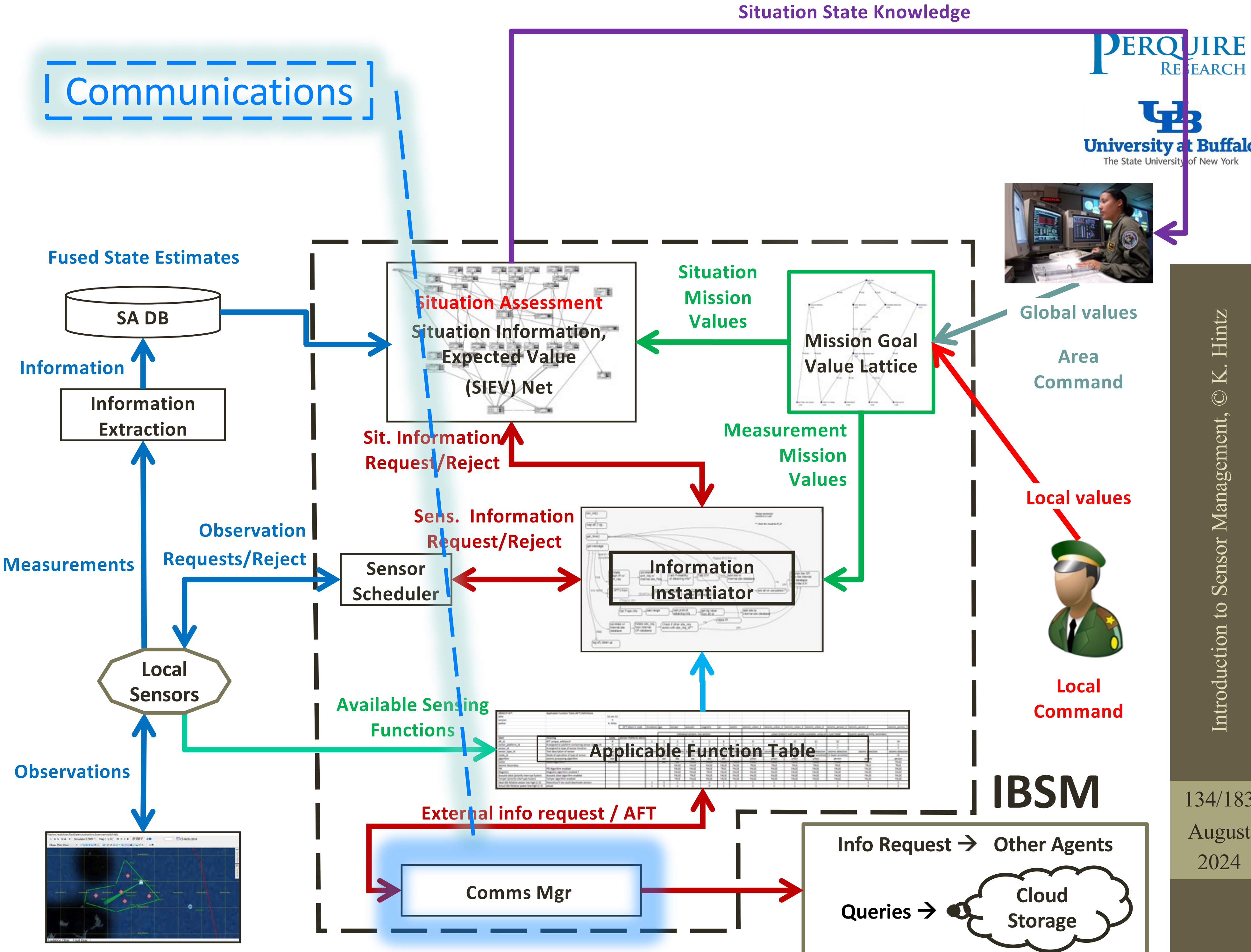
University at Buffalo
The State University of New York

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


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

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

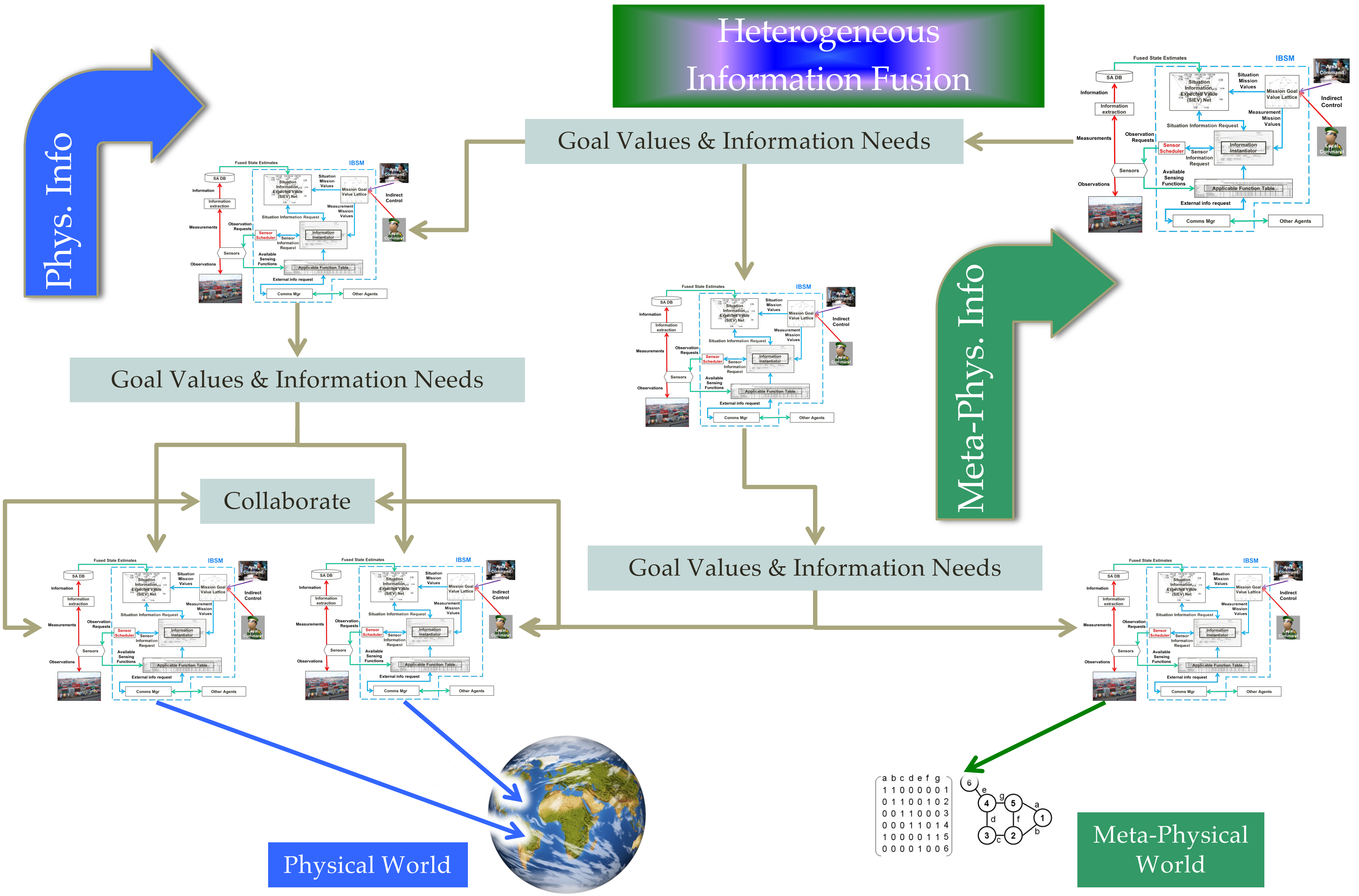
PERQUIRE RESEARCH

University at Buffalo
The State University of New York

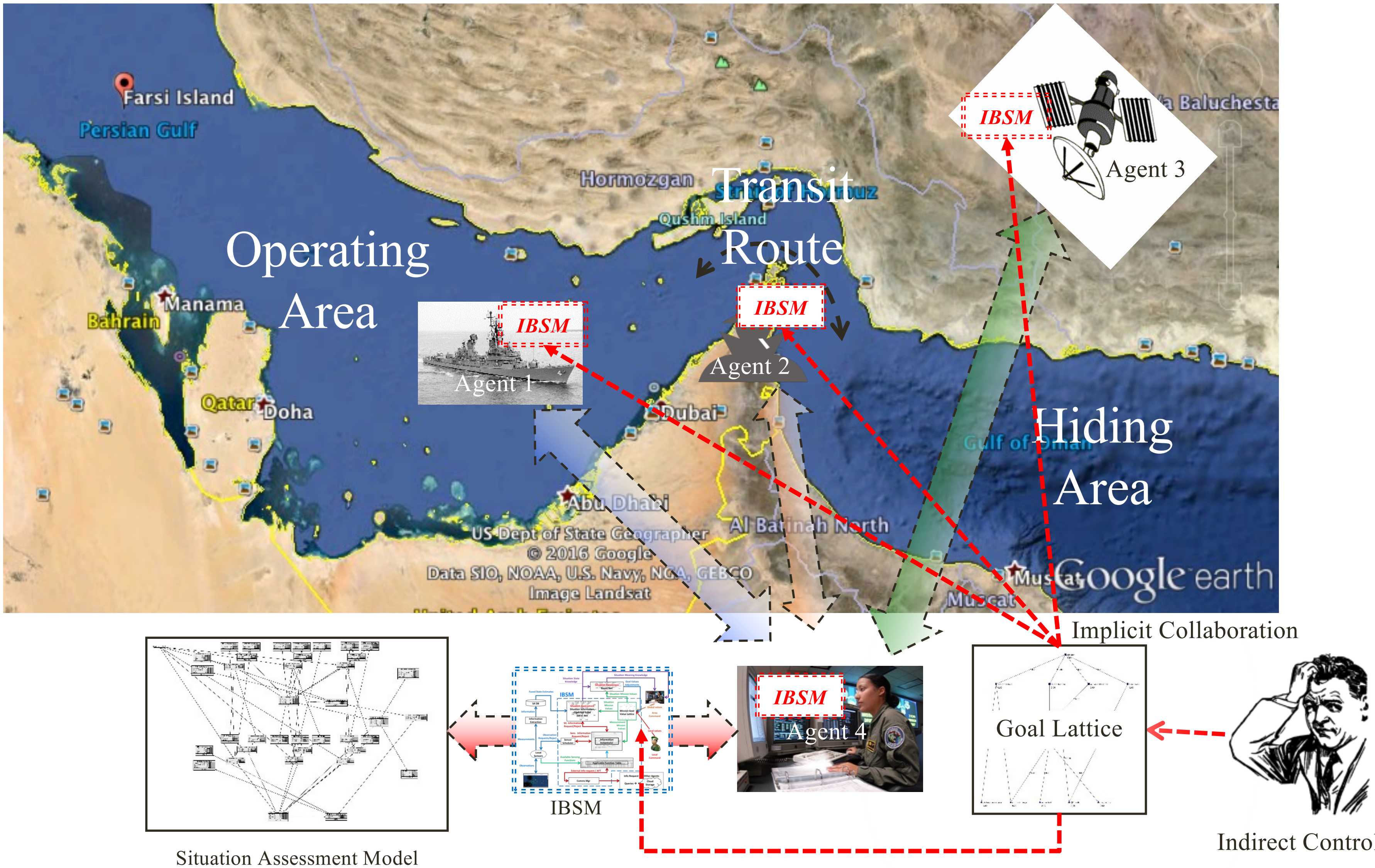
- ***IBSM concept is platform independent*** and can be used for theatre information acquisition as well as individual sensor platform management
- One ISR layer's sensors is another layer's squadron is another layers aircraft, …
- ***HOL operation*** is exercised through transmission of shared goals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

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

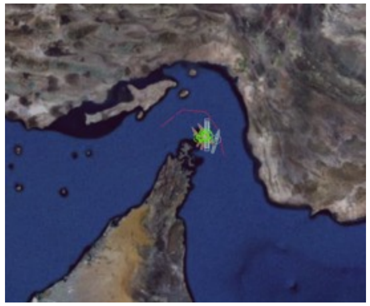
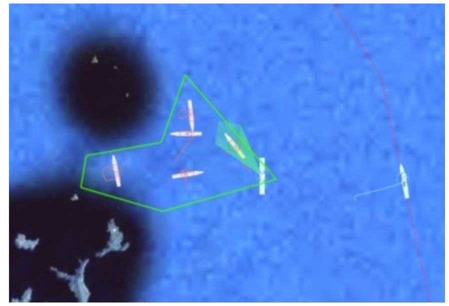
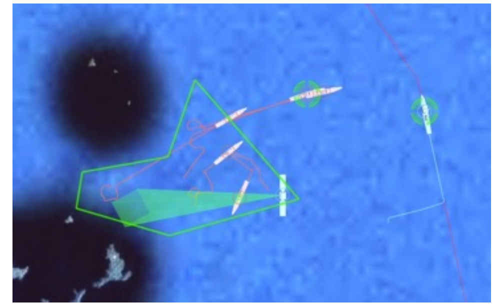
Perquire Research
University at Buffalo
The State University of New York



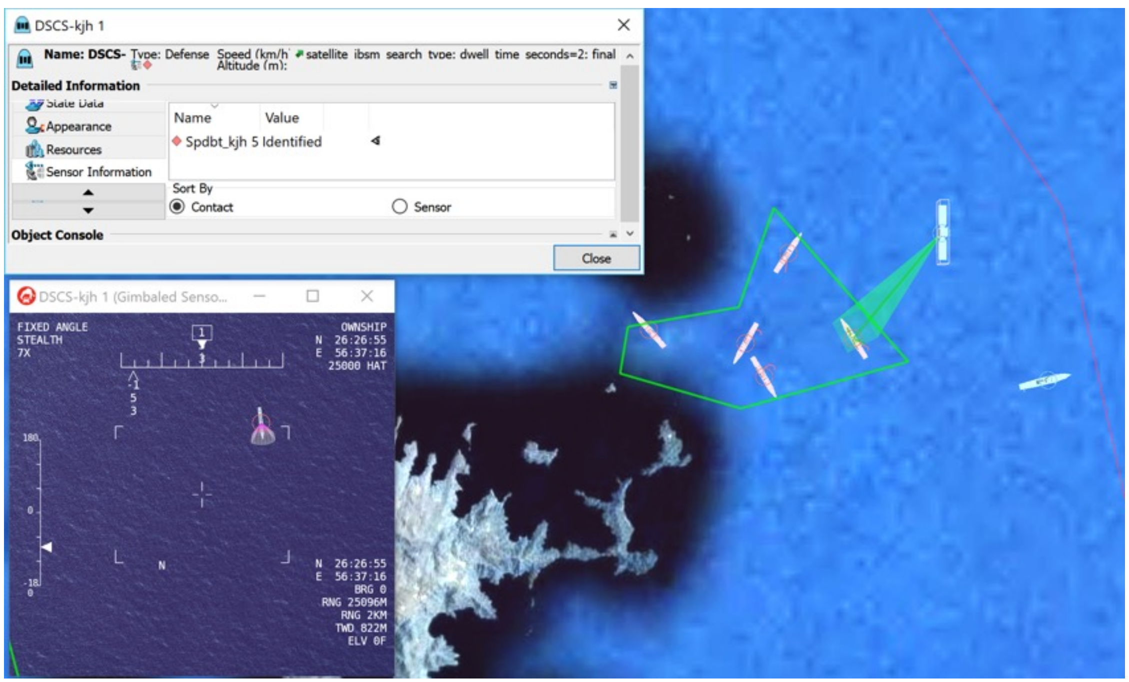
Reification of the Notional Spatial Model

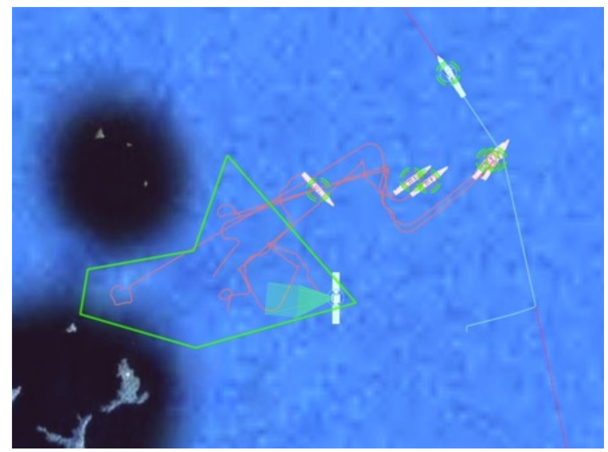


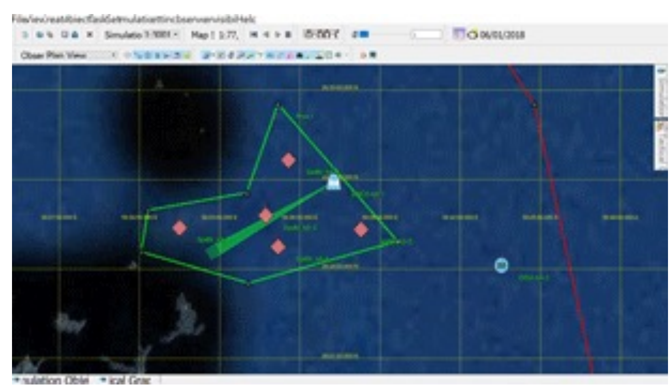
St. of Hormuz Scenario, Overhead Surveillance, Simulated in MAK, VR Forces

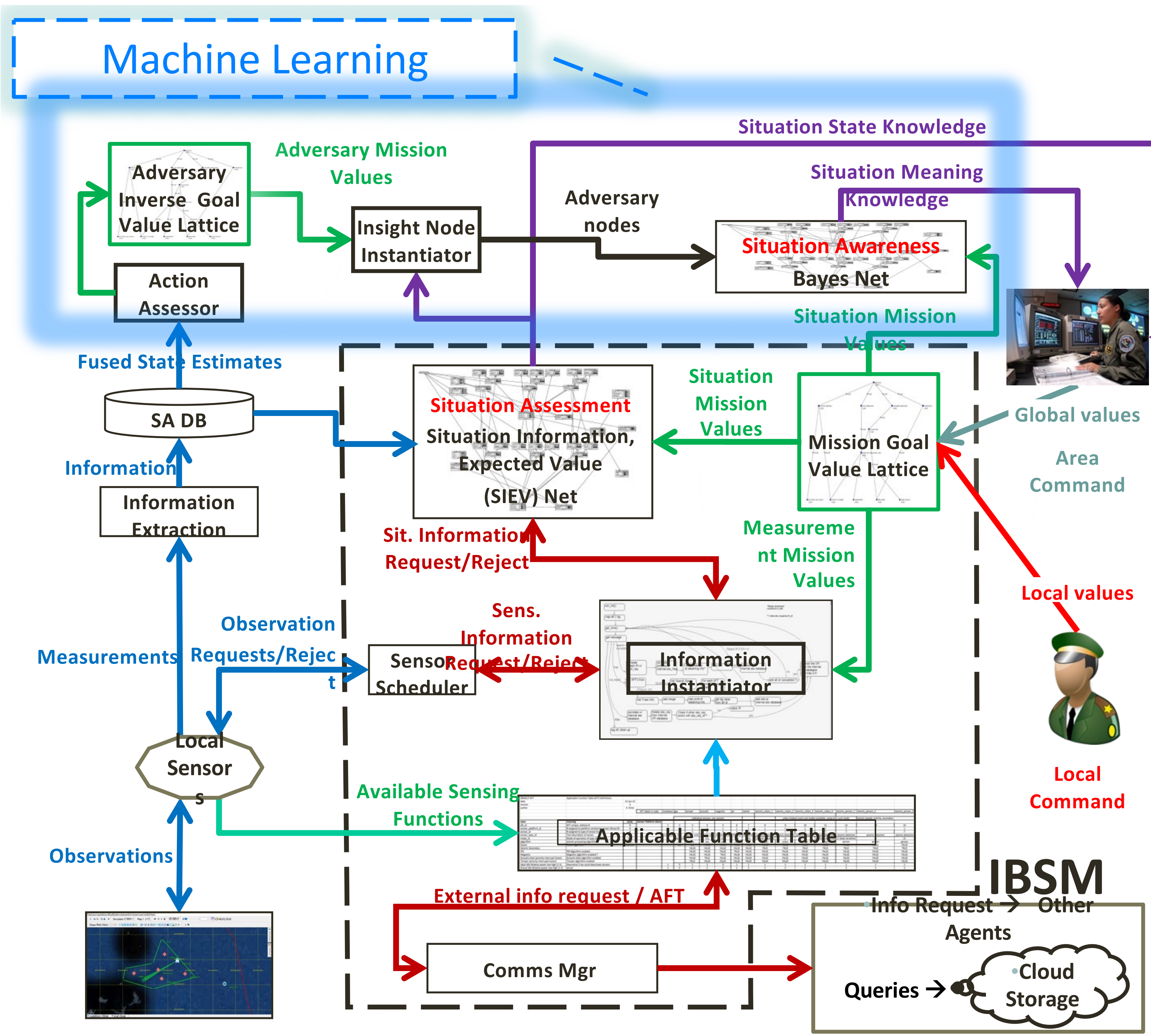





Speedboats random movement in area converting to attacking transiting DDG









Perquire Research
University at Buffalo
The State University of New York

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

PERQUIRE RESEARCH

University at Buffalo
The State University of New York

- 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

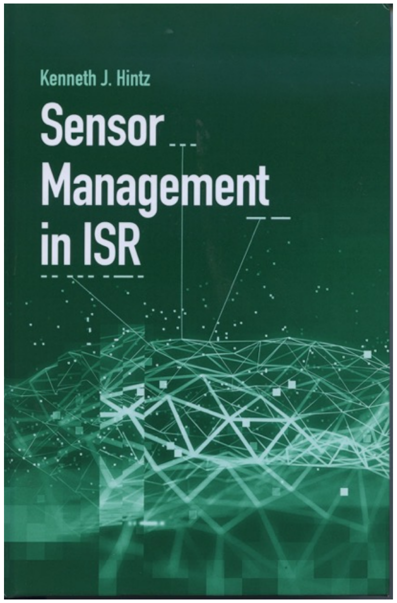
Summary: IBSM Is a ***Satisficing Solution*** To Multiplatform Heterogeneous Real-Time Sensor & Mission Management

PERQUIRE RESEARCH

University at Buffalo
The State University of New York

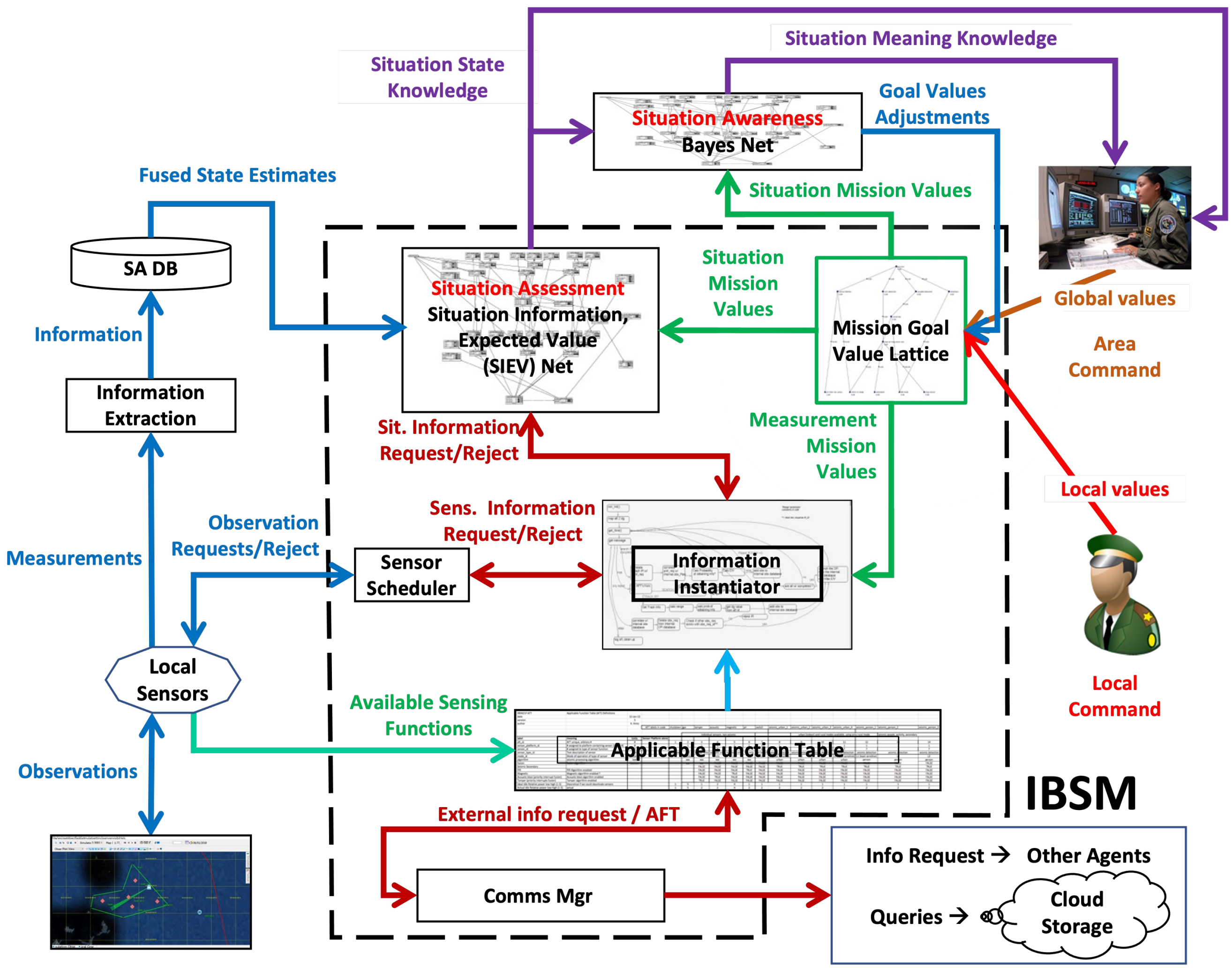
- ***Dynamically reconfigurable*** through use of ***applicable*** (sensor) ***function table***
- ***Information instantiator*** allows for ***one sensor management model*** to be the framework for multiple platforms and hierarchical levels of resource management
- Sensors can be added or removed in 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?



K. Hintz, *Sensor Management in ISR*, Boston:Artech House, 2020

https://perquire.com/tutorial/



PERQUIRE RESEARCH

University at Buffalo
The State University of New York

Short Break & on to KARPP/SOA