Maximal Information Systems

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ARC=Australian version of NSF

ARC Centre of Excellence for Autonomous Systems

The Thesis

- Large Scale "Systems of Autonomous Systems"
- We would like to:
  - Provide a quantitative model of system components
  - Reason *a priori* about combinations of components
  - Predict performance of complete systems

Information provides a measure for a large class of system designs

Information: A Reminder

- Entropic Information
  - Measures surprise
  - Is additive by construction

$$H_P(\mathbf{x}) = -E\left[\log P(\mathbf{x})\right]$$

- Mutual Information
  - Belief compression
  - Incorporates "context"

$$I(\mathbf{x},\mathbf{y}) = E\left[\log \frac{P(\mathbf{x}\mid\mathbf{y})}{P(\mathbf{x})}\right]$$

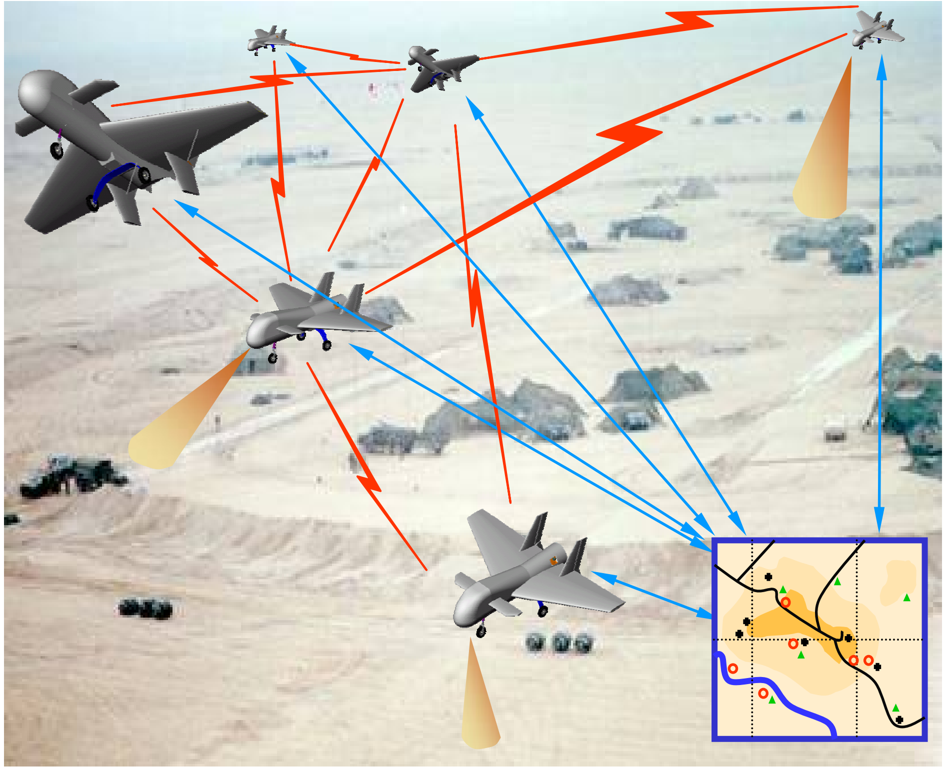
- Combinations are additions:
  - Sensing, control
  - Abstraction

$$H(\mathbf{x},\mathbf{y}) = H(\mathbf{x}) + H(\mathbf{y}) - I(\mathbf{x},\mathbf{y})$$

And now a story about information in systems of systems

Decentralised Data Fusion (DDF)

- Way back in 1988 …
- A set of network Data Fusion methods:
  - Ad Hoc Network
  - Fusion at Sensor/Platform
  - No Central Fusion Site
  - Fully Scalable
- Decentralised Algorithms:
  - Information-methods
  - For target tracking
  - For cooperative navigation
  - For cooperative control



The Information Filter

Bayes:

$$P\left(\mathbf{x}(k) \mid \mathbf{Z}^{k}\right) = C.P\left(\mathbf{x}(k) \mid \mathbf{Z}^{k-1}\right) \prod_{j} P\left(z_{j}(k) \mid \mathbf{x}(k)\right)$$

Log-Likelihood:

$$\ln P\left(\mathbf{x}(k) \mid \mathbf{Z}^{k}\right) = \ln P\left(\mathbf{x}(k) \mid \mathbf{Z}^{k-1}\right) + \sum_{j} \ln P\left(z_{j}(k) \mid \mathbf{x}(k)\right) + K$$

(Fisher or Canonical) Information form for Gaussians:

$$\hat{\mathbf{y}}(k \mid k) = \mathbf{P}^{-1}(k \mid k)\hat{\mathbf{x}}(k \mid k) \qquad \mathbf{i}_{j}(k) = \mathbf{H}_{j}^{T}\mathbf{R}_{j}^{-1}\mathbf{z}_{j}(k)$$

$$\mathbf{Y}(k \mid k) = \mathbf{P}^{-1}(k \mid k) \qquad \mathbf{I}_{j}(k) = \mathbf{H}_{j}^{T}\mathbf{R}_{j}^{-1}\mathbf{H}_{j}$$

Autonomous Systems

The Information Filter

Observation updates are simple sums (unlike KF):

$$\hat{\mathbf{y}}(k \mid k) = \hat{\mathbf{y}}(k \mid k-1) + \sum_j \mathbf{i}_j(k)$$

$$\mathbf{Y}(k \mid k) = \mathbf{Y}(k \mid k-1) + \sum_j \mathbf{I}_j(k)$$

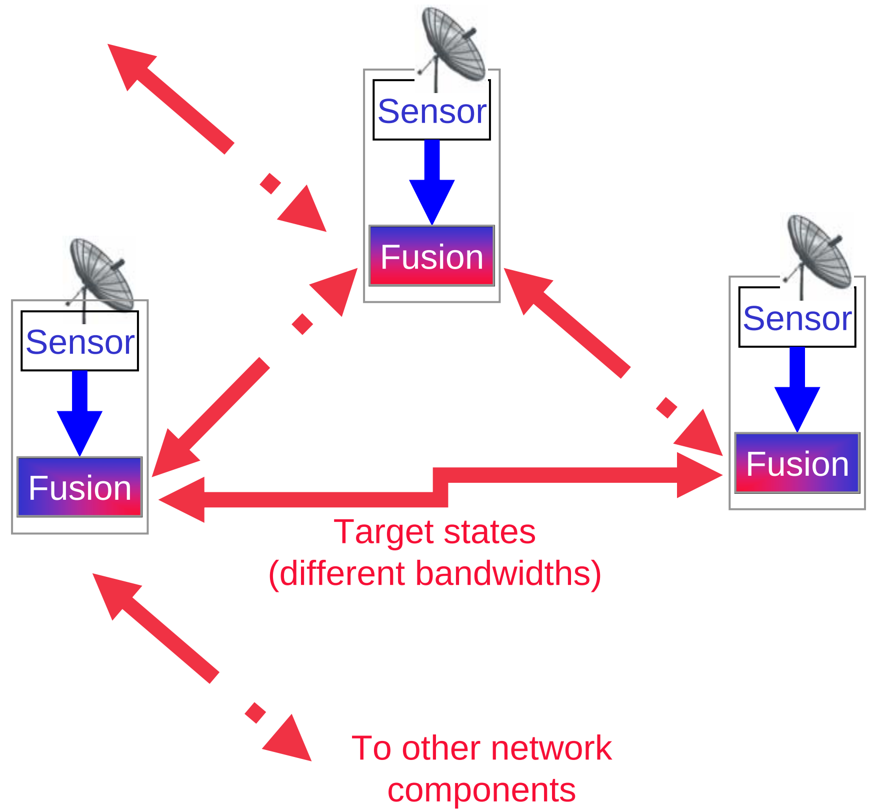
Time/Structure updates are Dual to state (KF) Observation Updates :

$$\hat{\mathbf{y}}(k+1 \mid k) = \hat{\mathbf{y}}(k \mid k) + \mathbf{\Omega}\left[\hat{\mathbf{y}}(k \mid k) + \mathbf{Y}(k \mid k)\mathbf{B}\mathbf{u}(k)\right]$$

$$\mathbf{Y}(k+1 \mid k) = \mathbf{Y}(k \mid k) - \mathbf{\Omega}(k)\mathbf{\Sigma}(k)\mathbf{\Omega}^T(k)$$

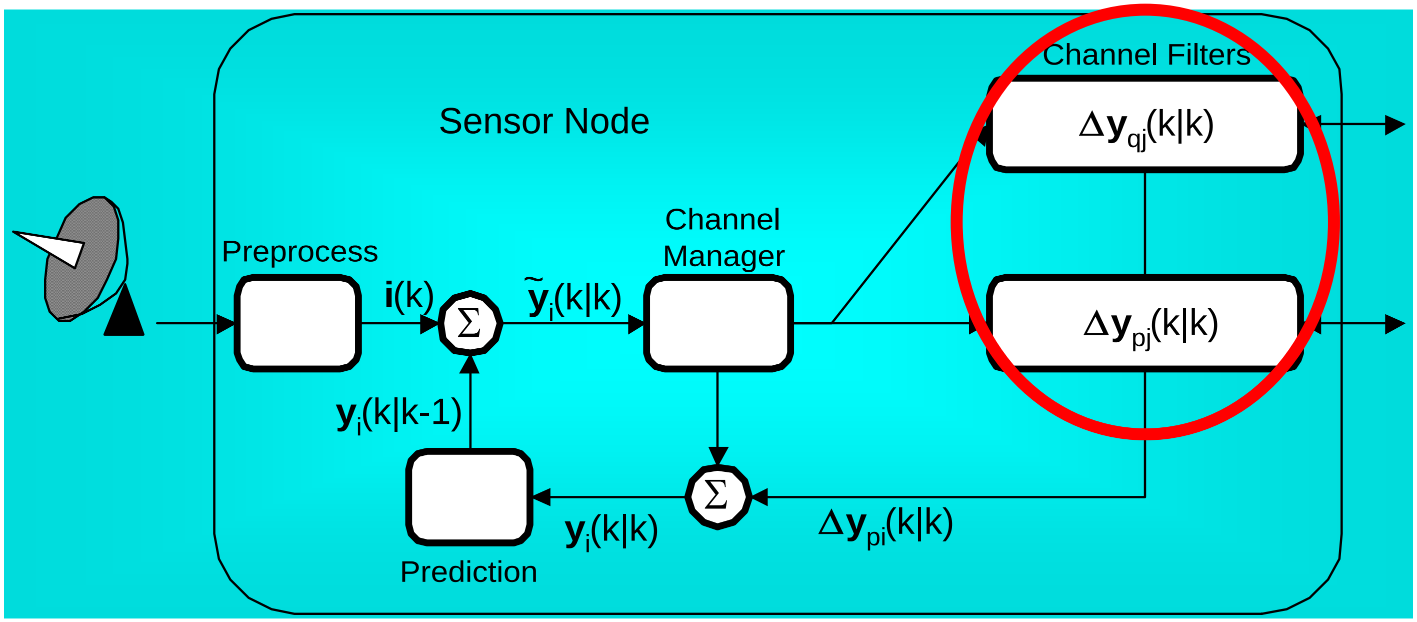
DDF: The Basic Idea

- Operation:
  - Fusion of local sensor data and communicated states
  - Common, re-configurable, ad-hoc network interface
  - No global fusion location
  - Fully scalable structure

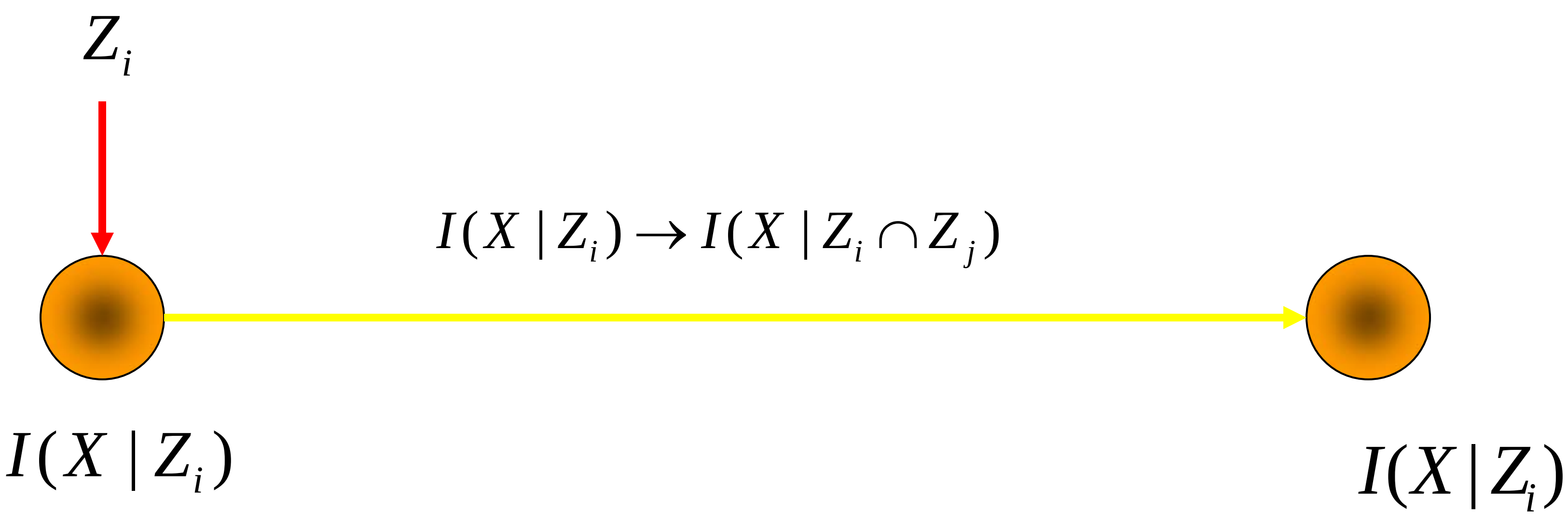


Operation of Sensor Nodes

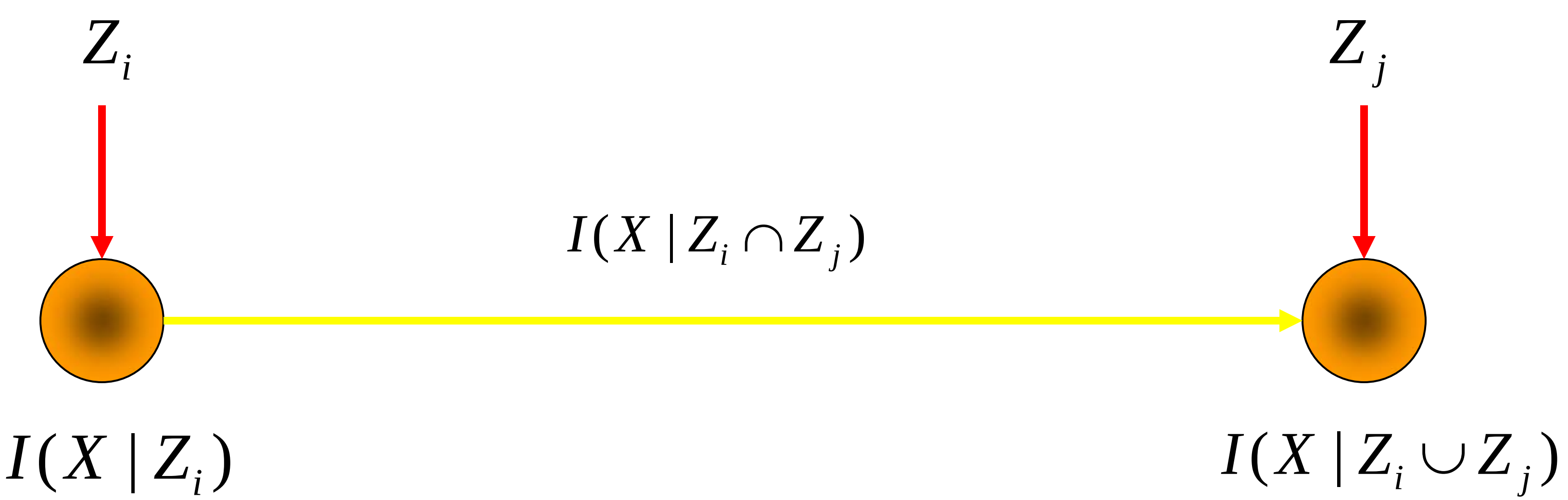
- Nodes fuse information from:
  - Local observations, Local predictions, and
  - Communicated information
- Focus on Channels:
  - Communicate local information gain (MI)
  - Assimilate information gains from neighbourhood



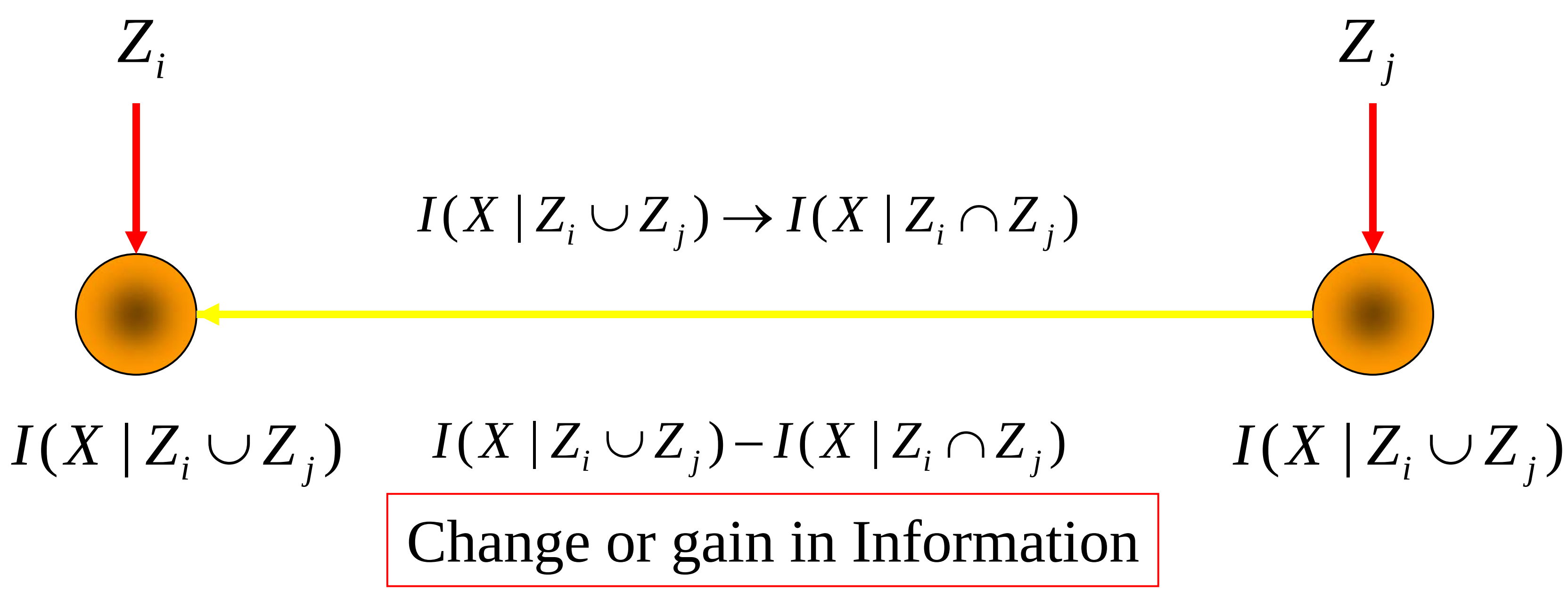
Operation of Channels



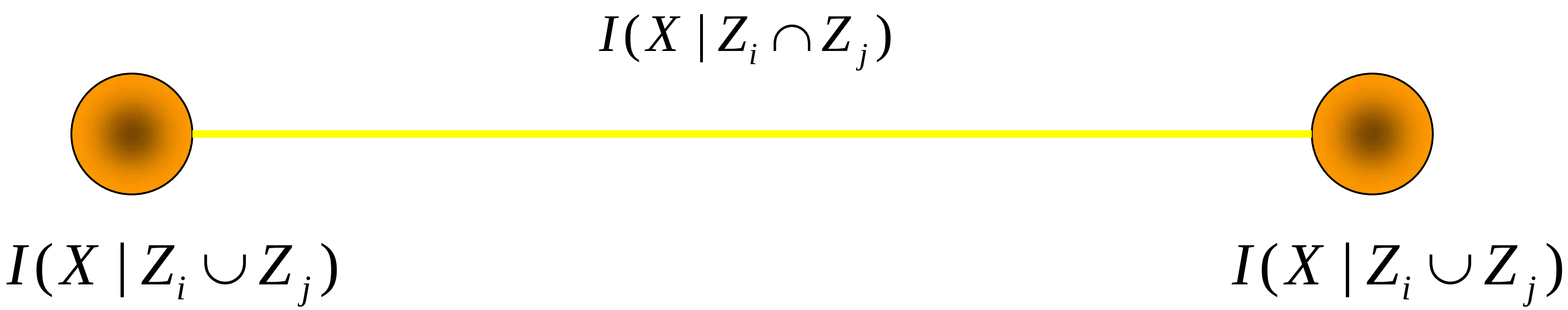
Operation of Channels



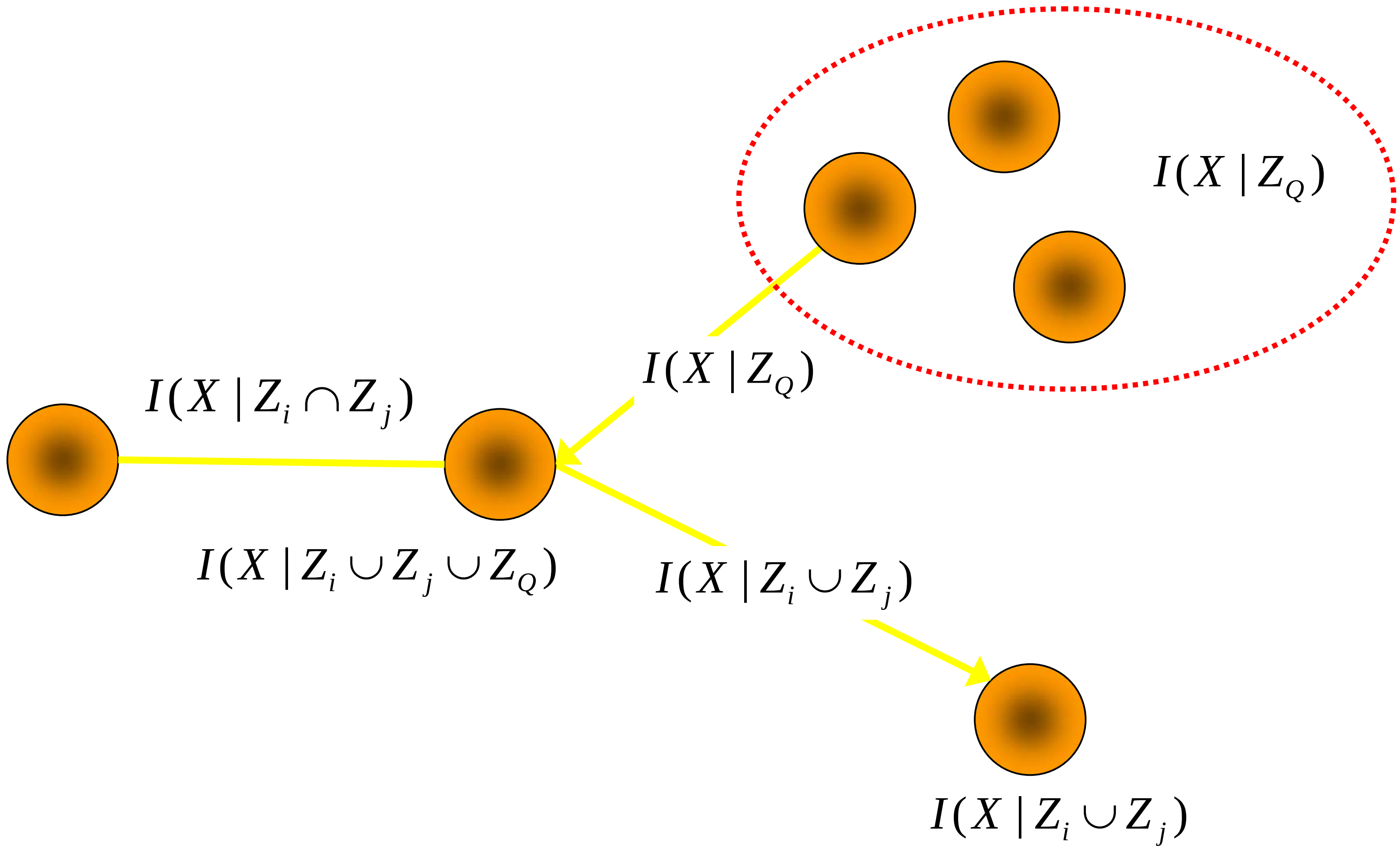
Operation of Channels



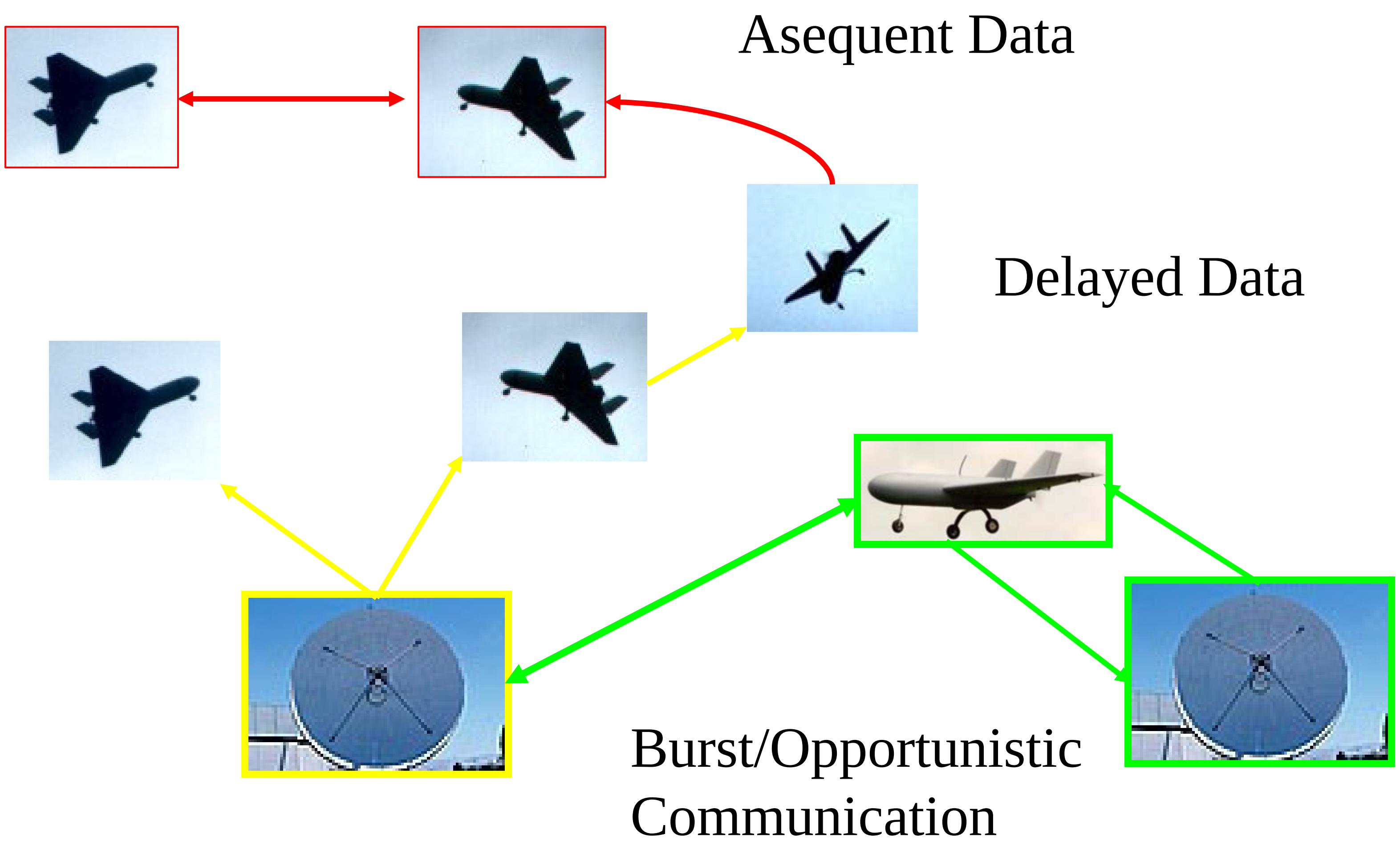
Operation of Channels



Scaling The Network

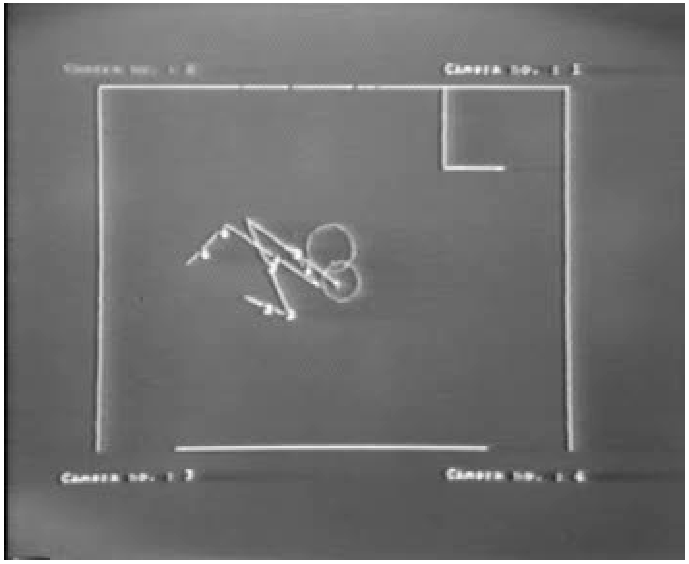


Issues of Timing

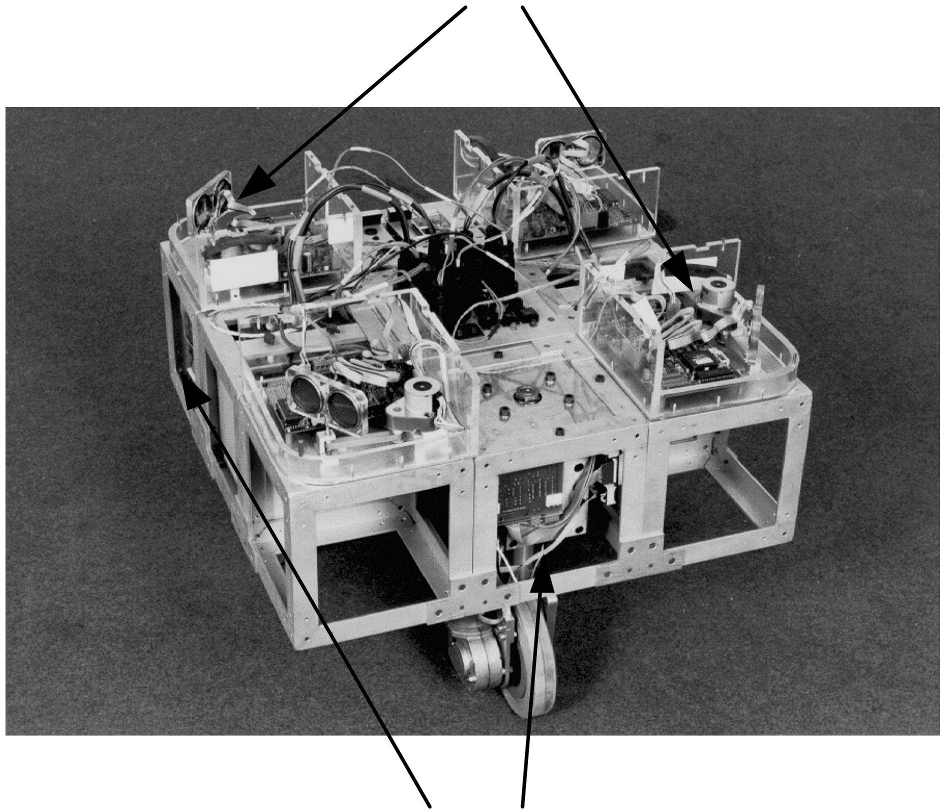


Early DDF Projects

- SKIDS (1986-1991): Prove essential idea
  - Distributed Tracking of people
  - Cameras, optical barriers, etc
- ISSS (1990-1994): Scalability
  - Large Scale Process plant
  - 250 distributed sensors
- OxNav (1991-1995): Modularity, management
  - Decentralised Navigation
  - Decentralised Sensor Management



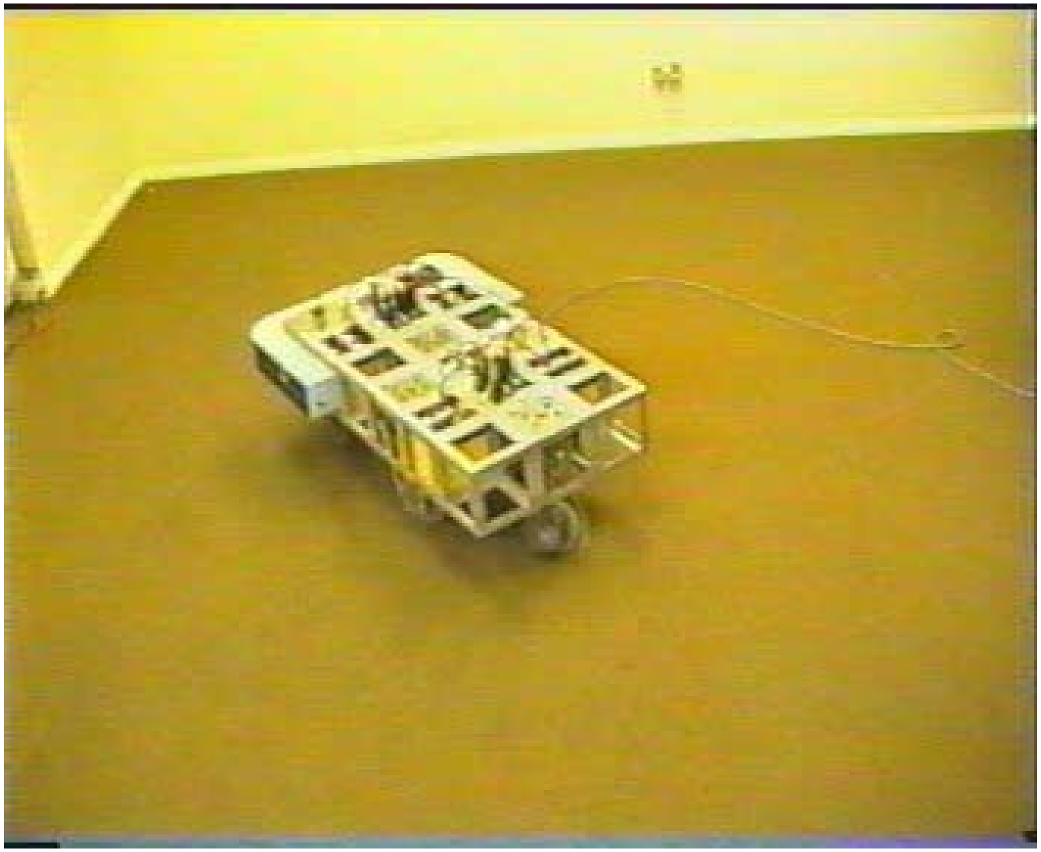
OxNav(1994): A system of modular information components



Navigation and Sensor Management

“Data Fusion and Sensor Management: An Information-Theoretic Approach”
J. Manyika and H. Durrant-Whyte, Prentice Hall 1994. Now only $900 on Amazon !

Modular Control



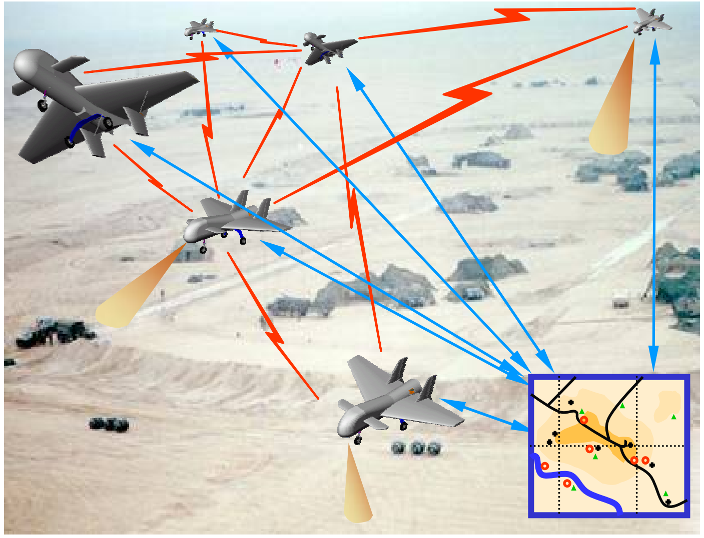
"Decentralised Control", Arthur Mutambara, CRC Press 1995

In 1995 nobody was interested in sensor networks
So I went to Australia to do Field Robotics
Then …

Autonomous Systems

ANSER I: Autonomous Navigation and Sensing Experimental Research

BAE SYSTEMS

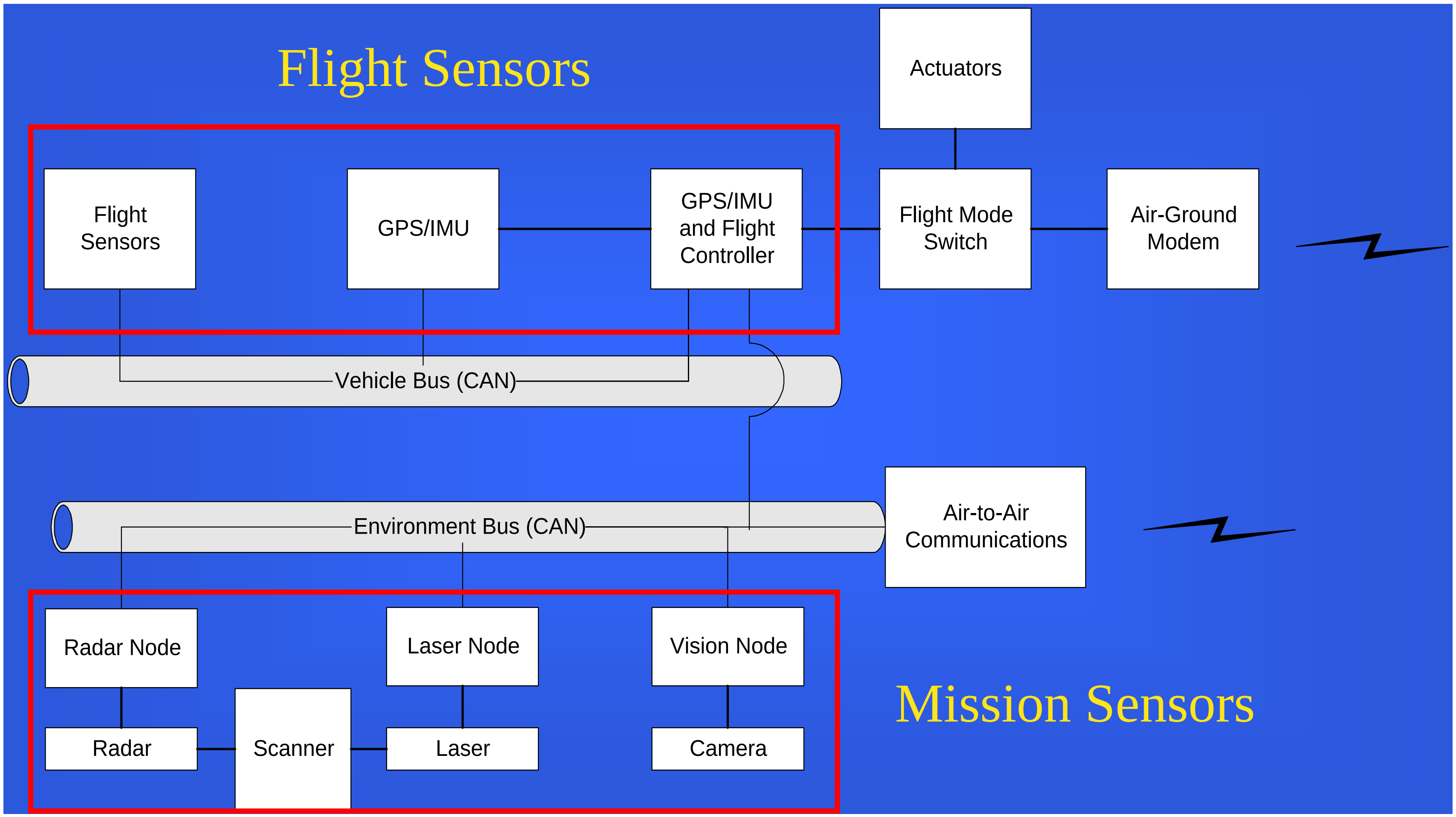


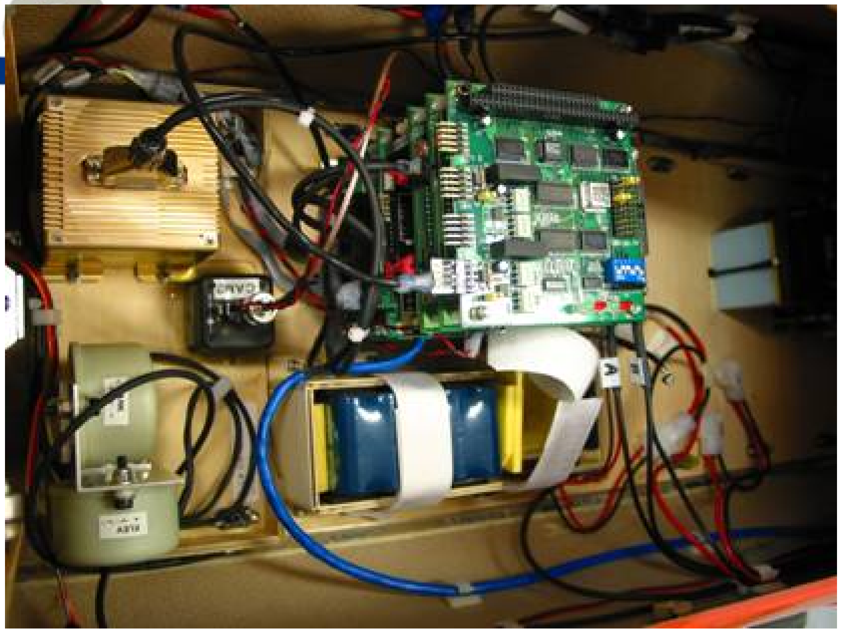
- **Objectives:**
  - To deploy a fully decentralised data fusion system on a group of four or more UAVs
  - To demonstrate functions of target tracking and simultaneous localisation and mapping, decentralised on many sensors in a network of platforms
  - To demonstrate, algorithmically and practically, key network-centric features: Modularity, Scalability, Flexibility and Survivability

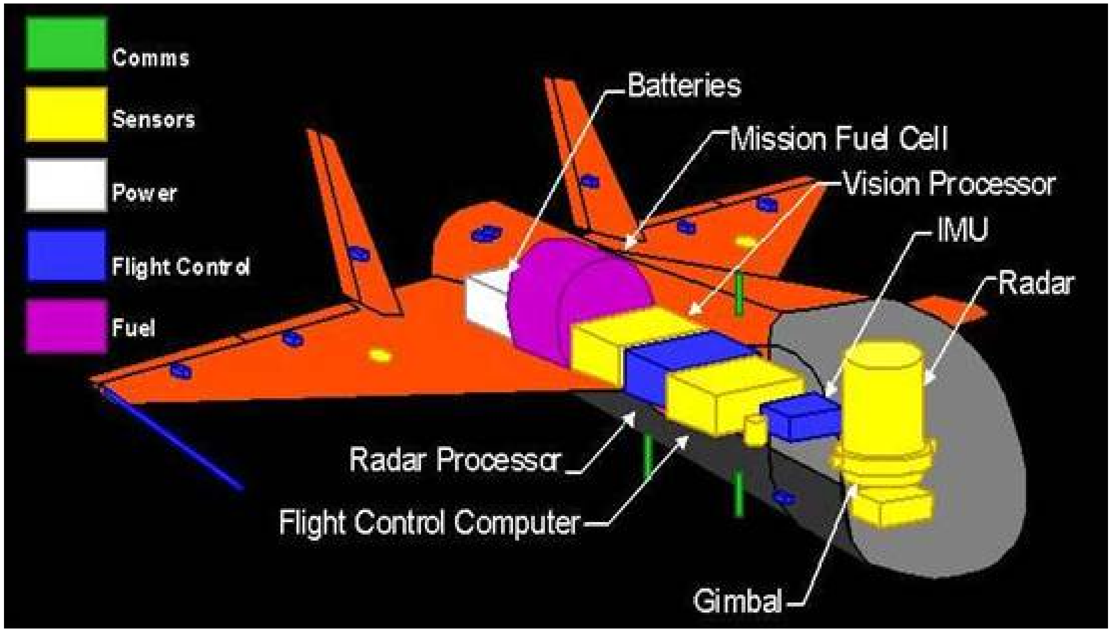
Flight Platforms

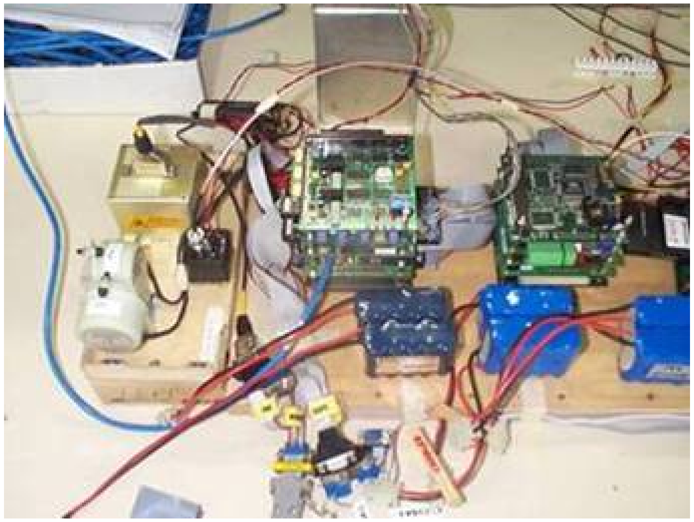
- Four Platforms – Delta Wing Configuration
- Max Speed – 80kts
- Payload Capacity – 20kg
- Wing Span – 3m
- Multiple Sensors per platform
- All modular pay-loads
- All parts interchangeable

On-Board Components

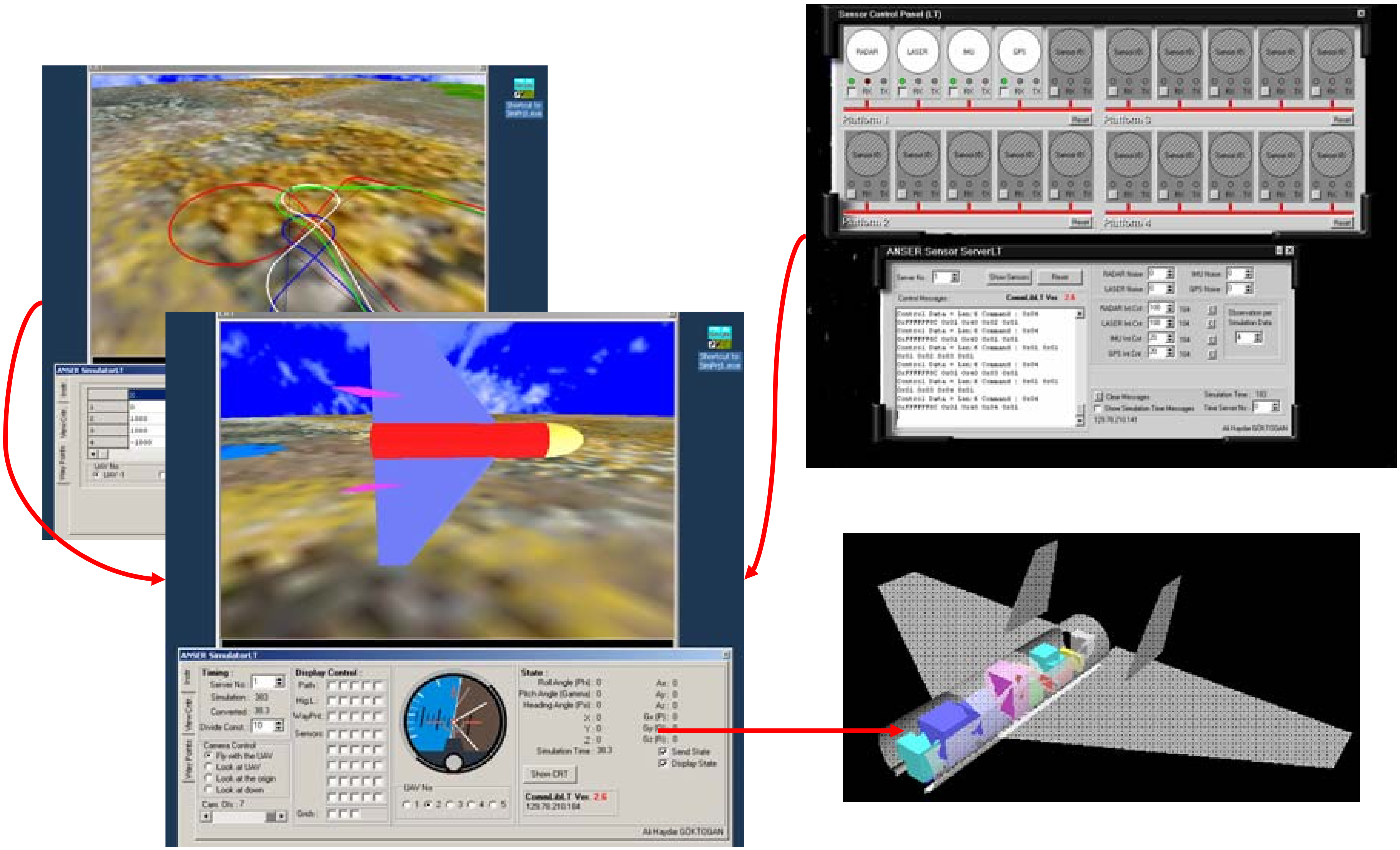





Comms
Sensors
Power
Flight Control
Fuel
Batteries
Mission Fuel Cell
Vision Processor
IMU
Radar
Radar Processor
Flight Control Computer
Gimbal



Mission Planning System



Multi-Vehicle Flights (2000-2001)

ANSER I: Conclusions

- **Information Communications is key**:
  - Timing, delay, asequent and burst communication
  - Maintaining integrity, extensible network operation
  - Channel and information management
- **Data Fusion issues**:
  - Registration and platform bias estimation
  - Cross-platform data association
  - Weak target information not captured well by information filter alone
- **Non-technical issues**
  - BAE Systems Chairman's Gold Award
  - Output integrated in a number of BAE Systems UK, US and Australian defence programmes

Decentralised Control

- Mutual Information as a metric for sensor management and control ?
- Maximise the gain in information:
  - Tracking
  - Exploration
  - Search
  - …

Mutual Information Gain as a Control Metric

- Mutual Information is an *a priori* measure of average Information gain following observation

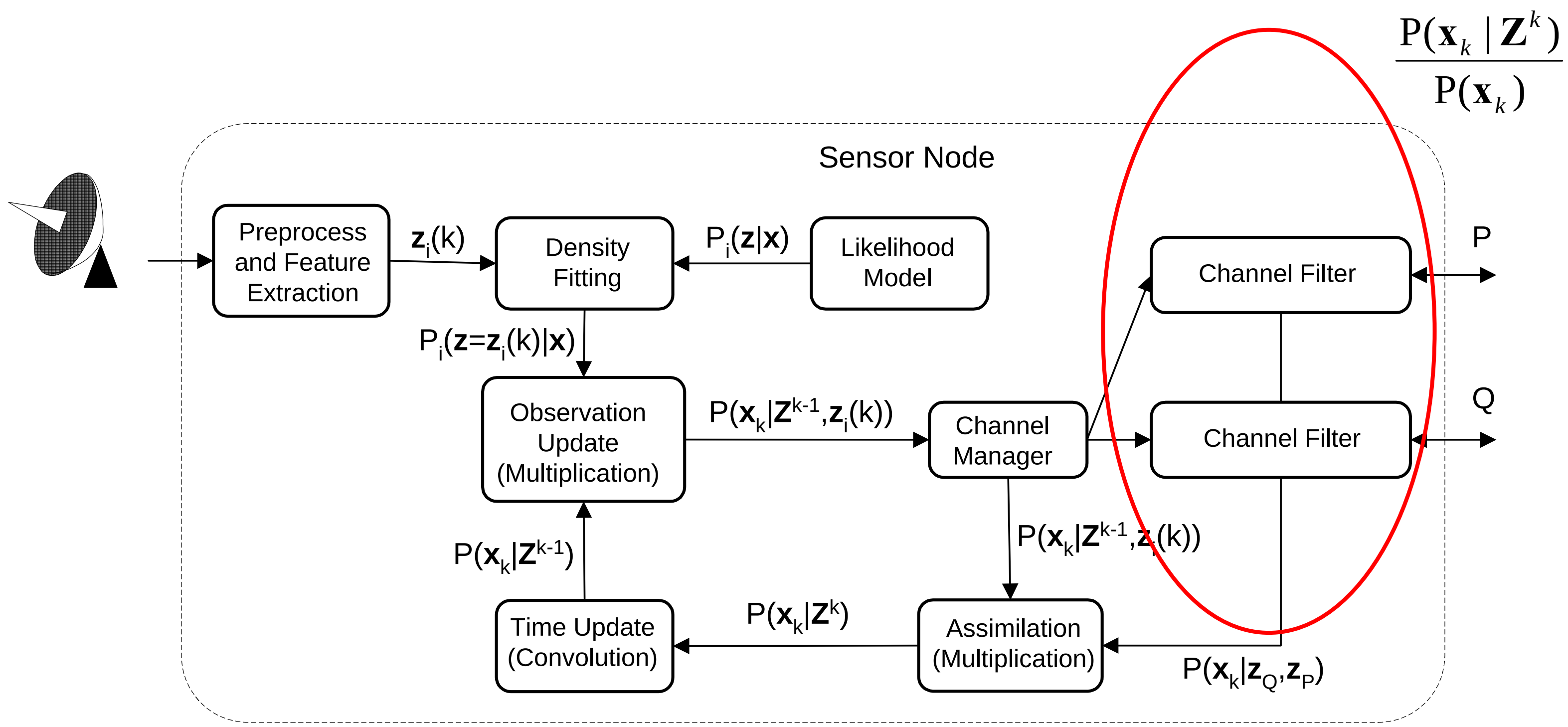
$$I(\mathbf{x}(t):\mathbf{z}(t)) = \mathrm{E}\left[\log\left(\frac{\mathrm{P}(\mathbf{x}(t)\,|\,\mathbf{z}(t))}{\mathrm{P}(\mathbf{x}(t))}\right)\right]$$

Measures "compression" of posterior density

- Choose the sequence of observations z(*t*) which maximise mutual information gain over a horizon
- Observations depend on platform state x(t)
- State is governed by some control input u(t)
- Choose u(t) to maximise information gain

Mutual Information in DDF

- Mutual Information or information gain, is exactly what is communicated in the DDF !
- Can be easily exploited in sensor management, communications and platform control

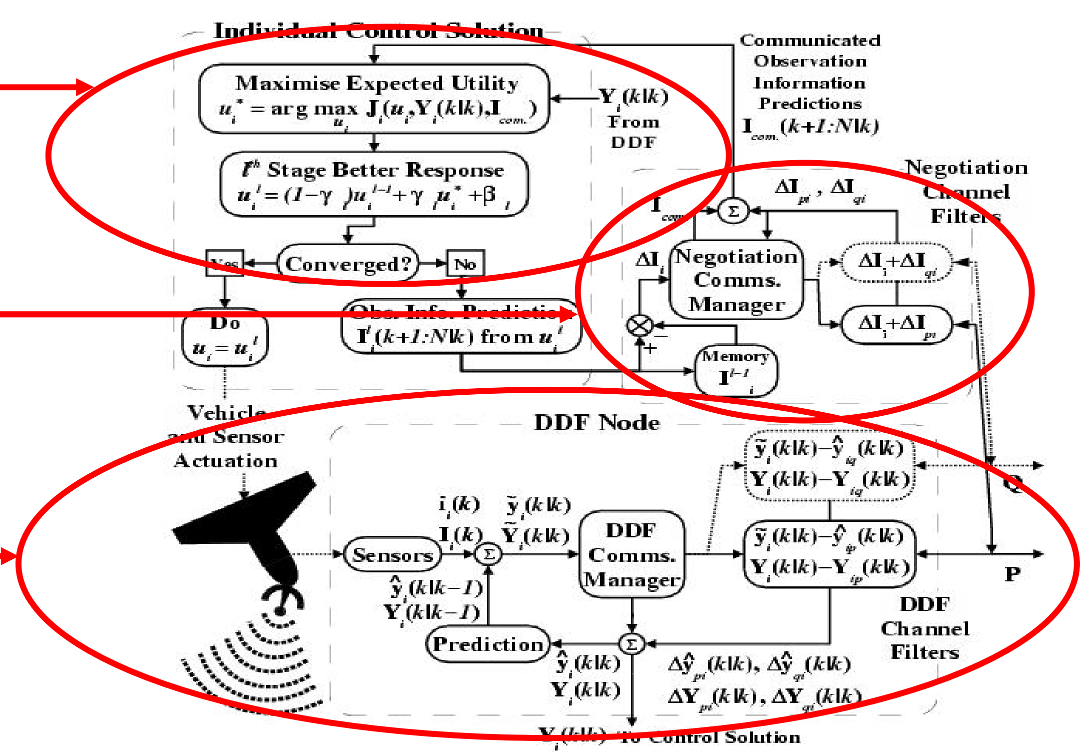


Information and Systems Design

Local Controller

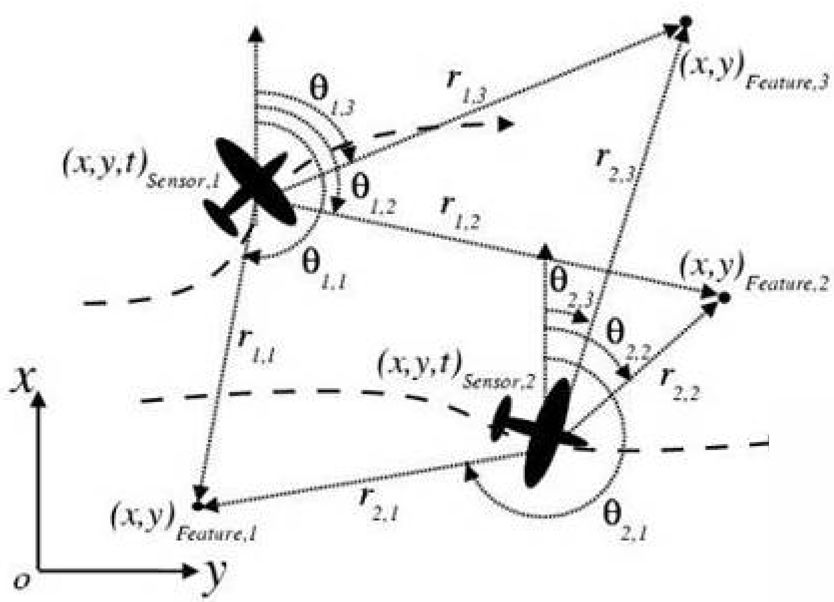
Internode Negotiation

Conventional DDF Node



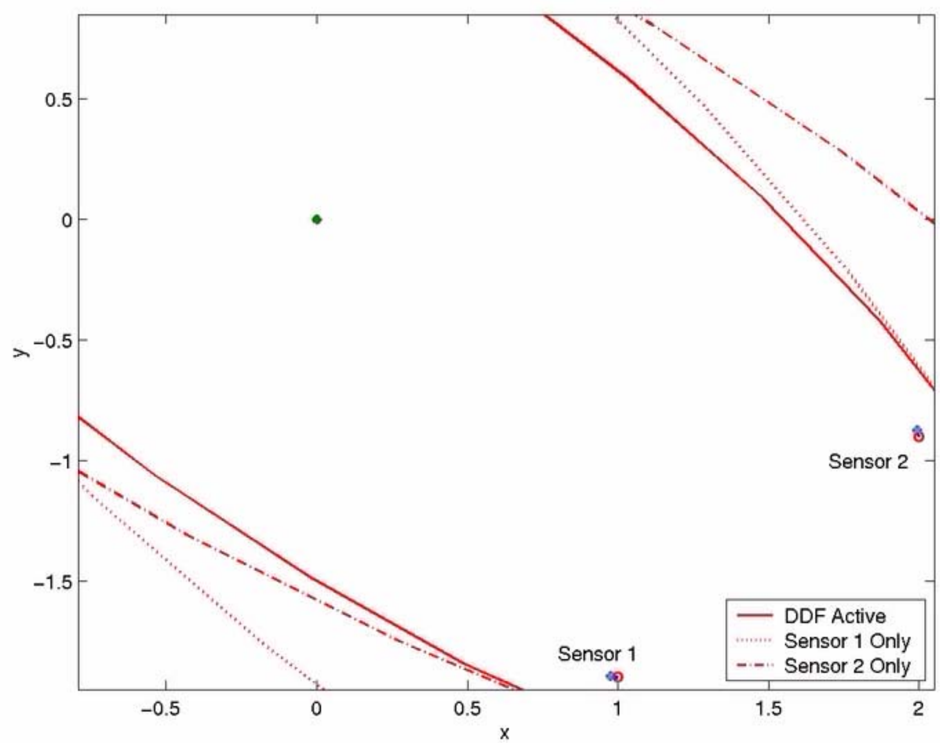
Ben Grocholsky, PhD U. Sydney 2002

Example Cooperative Control



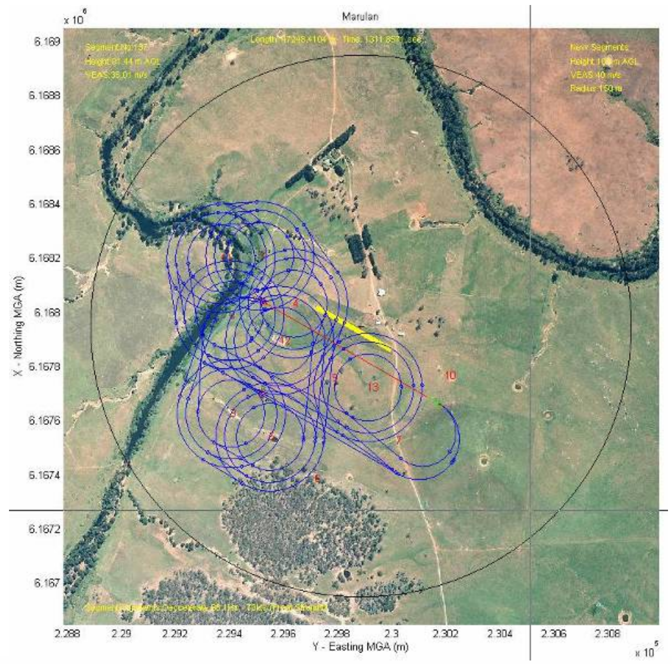
- The trajectory that maximises information
- Information shared (DDF)

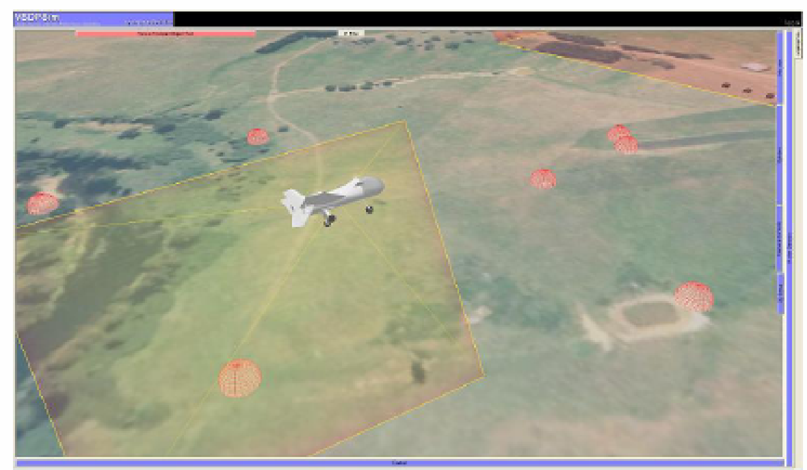
- Inherits DDF properties:
  - Scalability
  - Survivability



Future Cooperative UAVs

- How best to use tactical UAV fleets ?
- A list of candidate targets of interest
- Coordinate a UAV fleet with mixed sensors to:
  - Locate,
  - identify and
  - prosecute targets
- Demonstrate this





Set-up

- DDF Enabled on all platforms
- Mutual information on target location and IDs
- A set of UAV manoeuvres:
  - Point-to-Point
  - Orbits
- K-step look-ahead

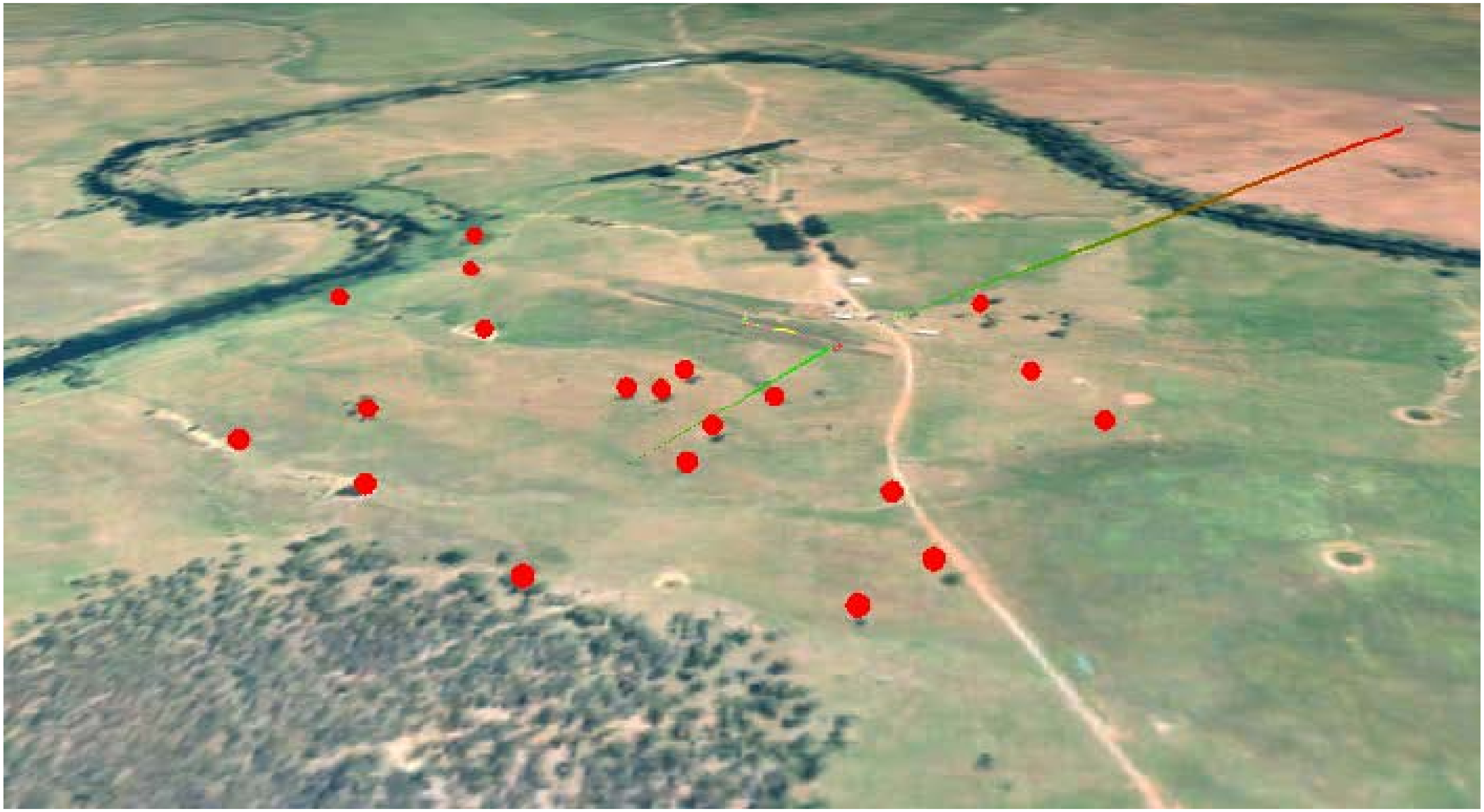
$$\mathbf{I}_{Orbit} = \frac{R\omega}{V} \int_{\varphi s}^{\varphi_e} \mathbf{I} d\varphi$$

Targets

Cooperative Demonstration

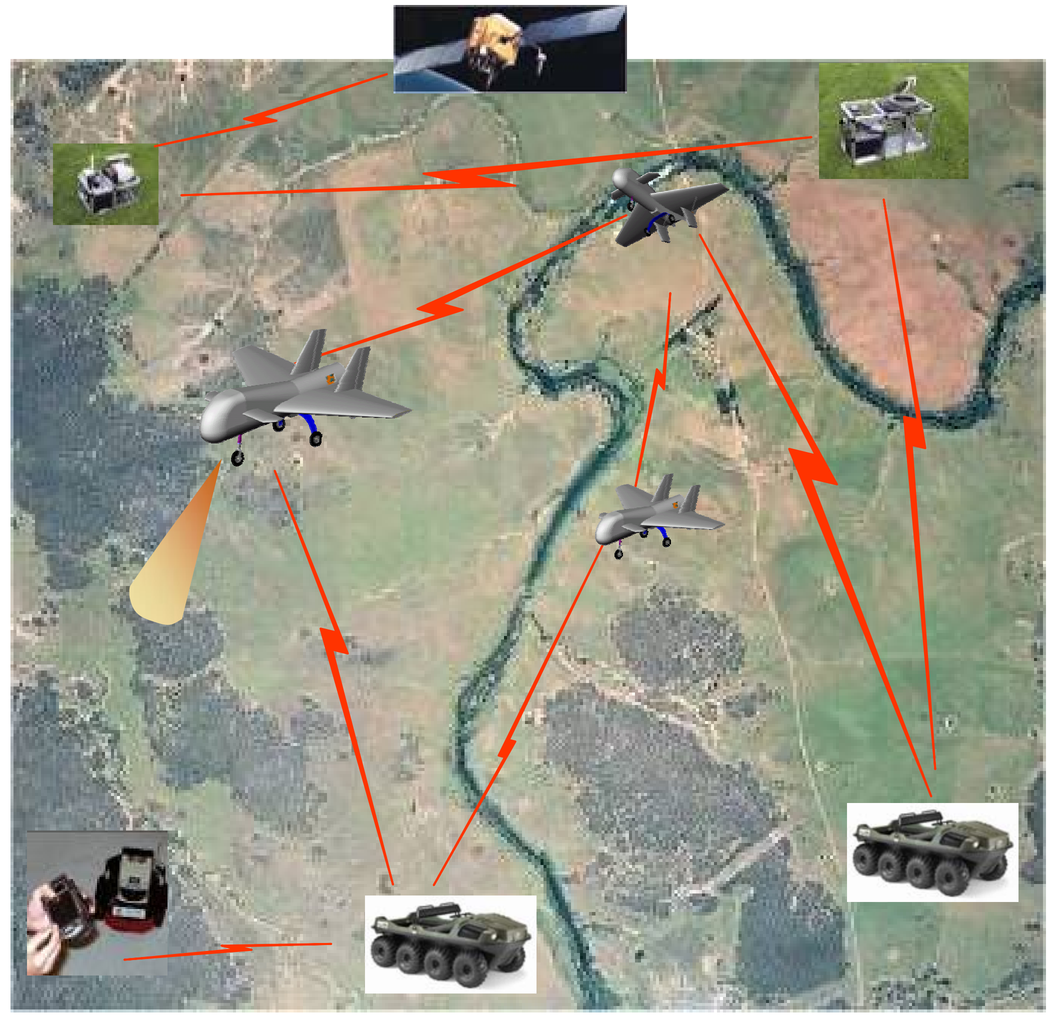
Two Vehicle Demonstration

From the Ground Station



ANSER II - Aims

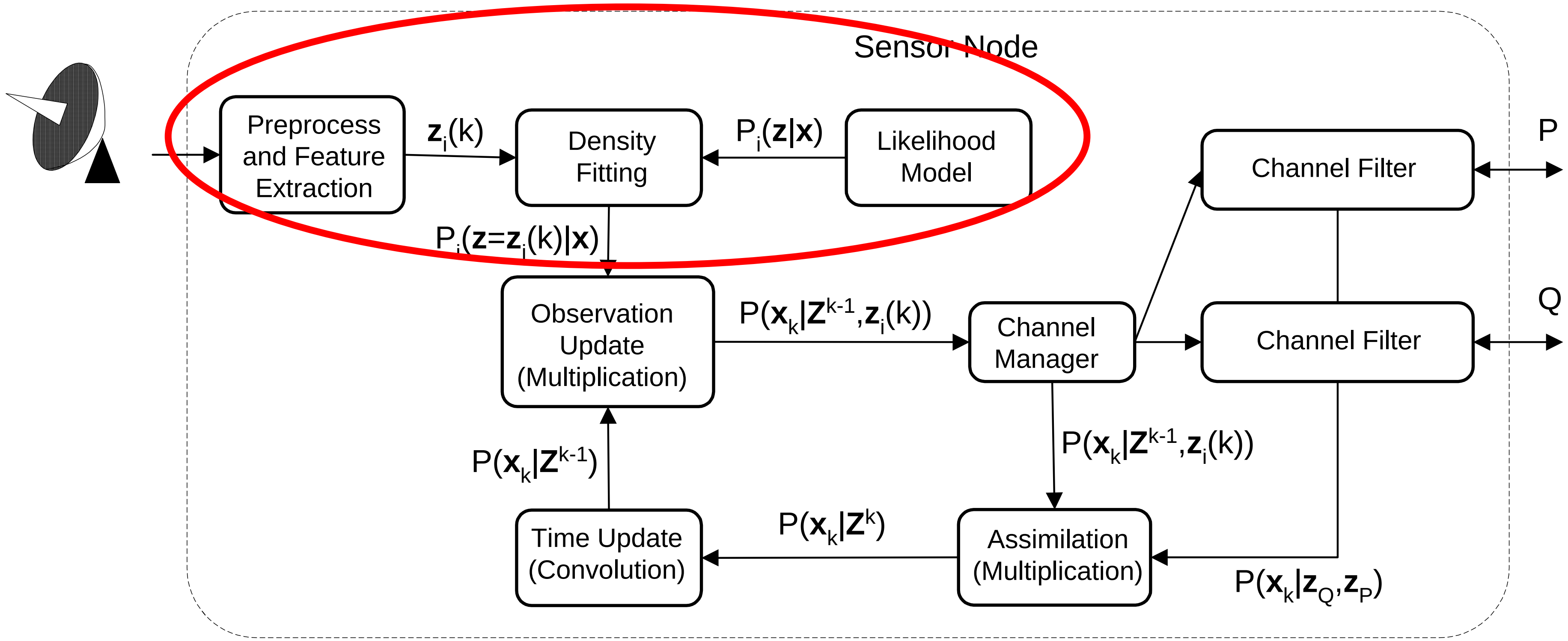
- Develop a general mathematical framework for probabilistic fusion in information networks.
- Address issues of efficient information communication and assimilation in information fusion networks.
- <u>Develop explicit models of node performance and use these in designing and building networks of “systems of systems”.</u>
- Demonstrate these in combined air/ground human/autonomous sensory networks



ANSER II Demonstration Project (2004-06)

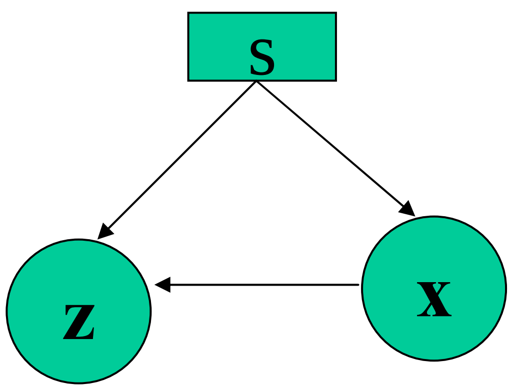
- Full Bayes DDF for fusion of heterogeneous data from UAVs, UGVs, human and data base sources
- Model general feature types; trees, buildings, dams, etc
- Identify and label features, integrate human inferences
- Real-time exploitation of network data by air, ground, human

Bayesian DDF Node Structure

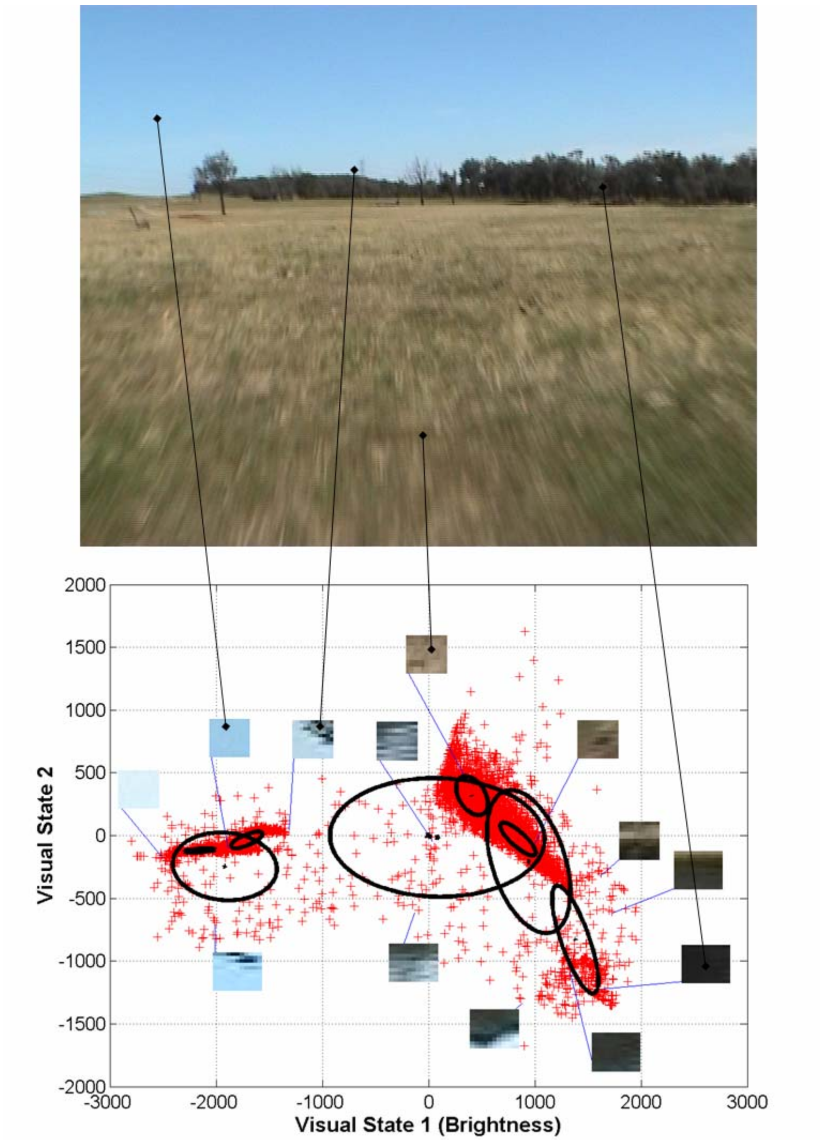


Step I: Model Generation

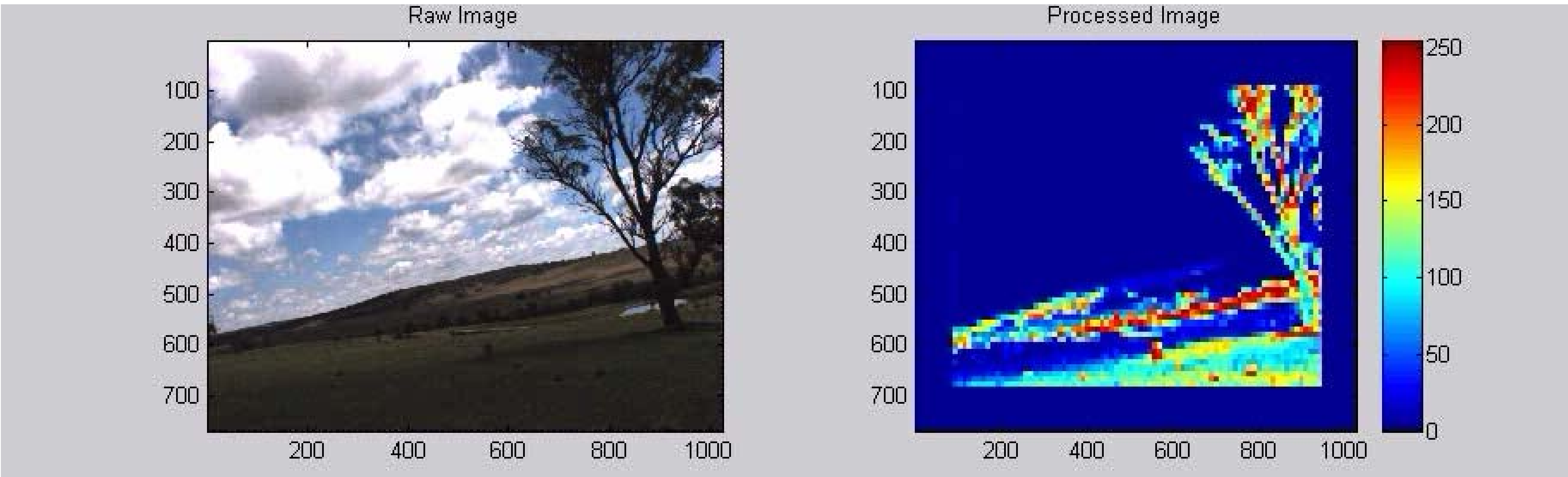
- NLDR (ISOMAP) on image patches
- Find low-D representation for significant patches of interest
- Use VBEM to find number and centre for mixture model



$$P(\mathbf{z},\mathbf{x},\mathbf{s}) = P(\mathbf{z}\mid\mathbf{x},\mathbf{s})P(\mathbf{x}\mid\mathbf{s})P(\mathbf{s})$$

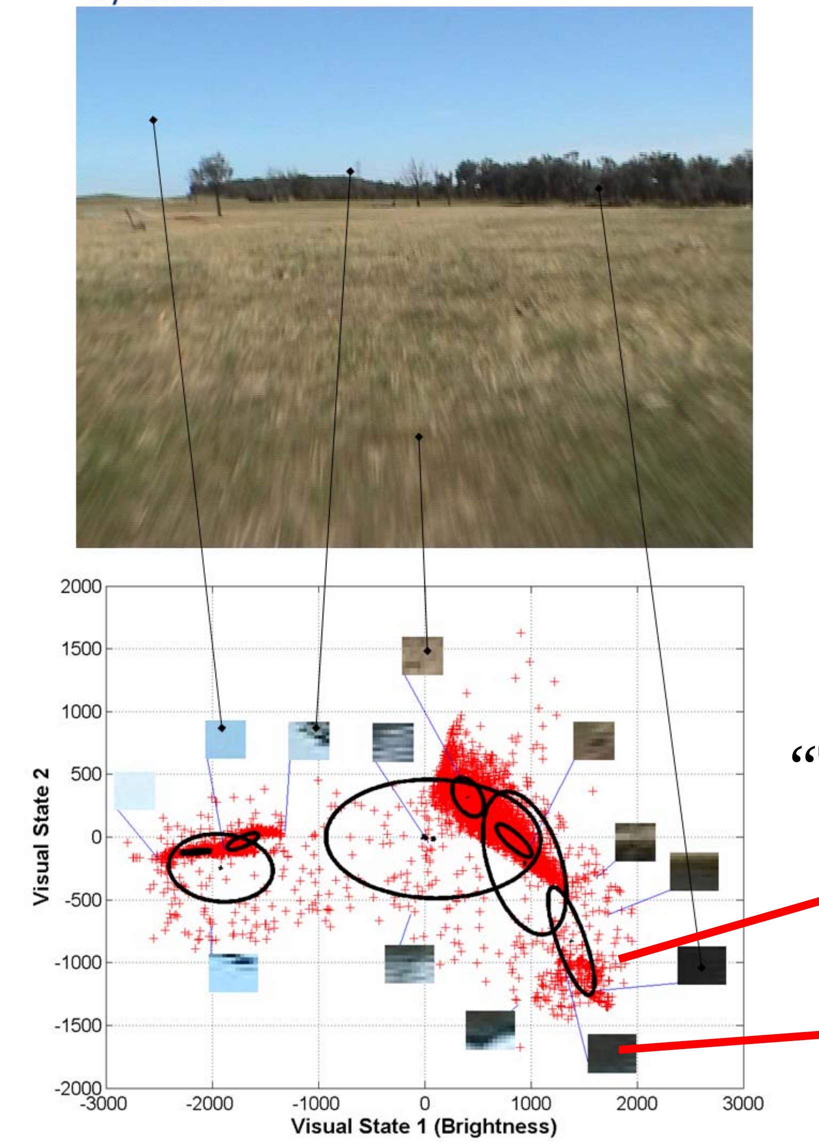


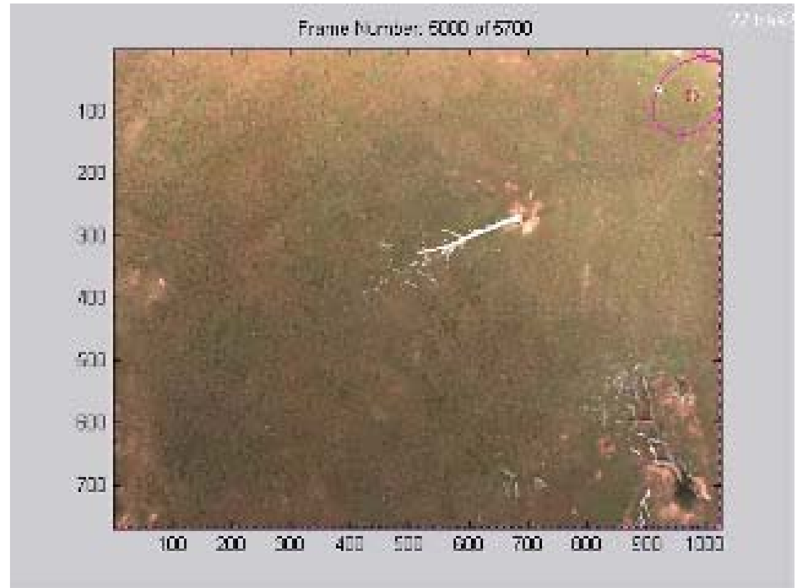
Step II: Model Inference



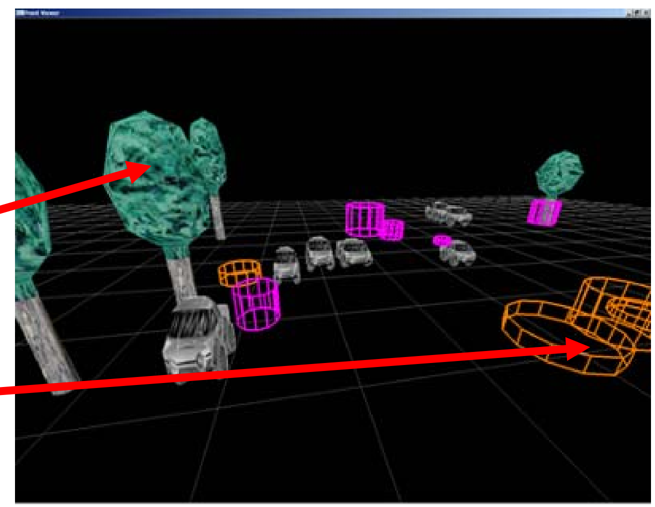
$P(\mathbf{z} \mid \mathbf{x},\mathbf{s})=P(\mathbf{z}|\mathbf{x}=[\mathbf{x},\mathbf{s}])$ is the required likelihood for inference

Step III: Assigning Labels





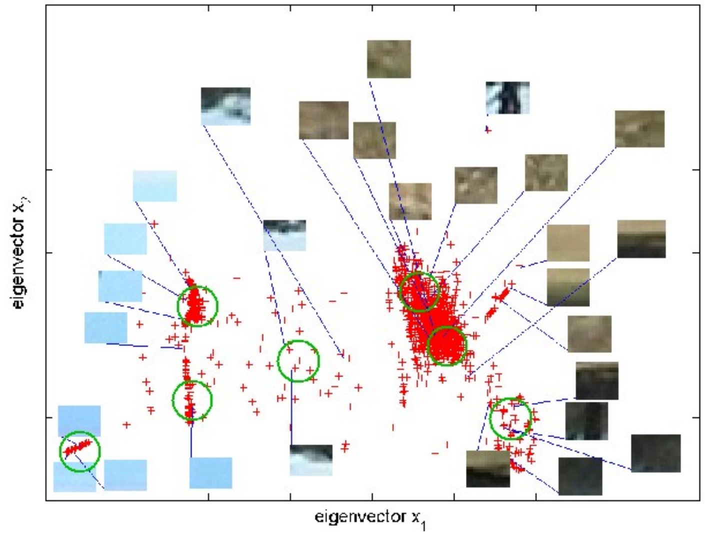
“Tree”

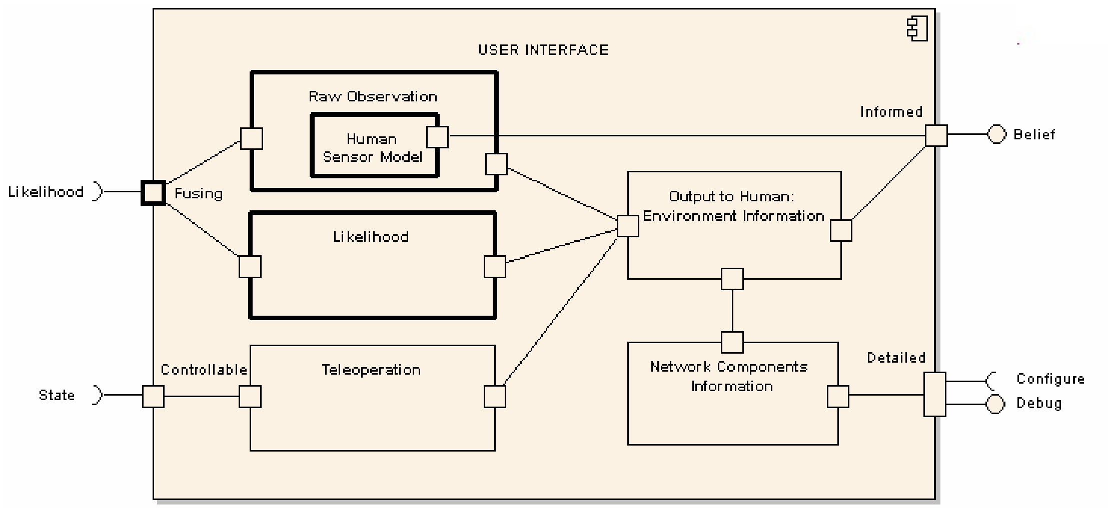


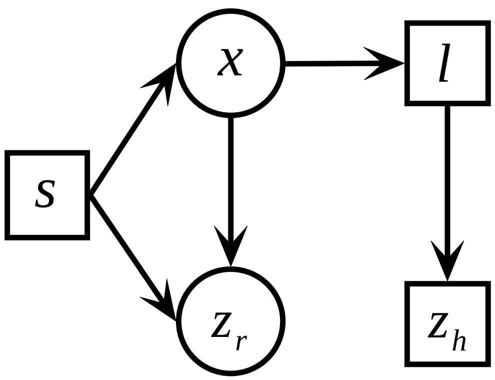
“Stuff”

Human DDF Node

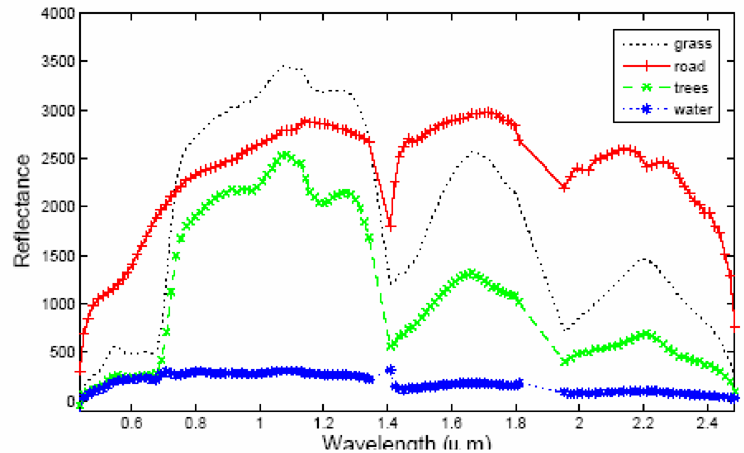
- Human operator input:
  - Metric Information
  - Labels
  - Context
- On-line estimation of "operator likelihood"
- Anonymous network queries

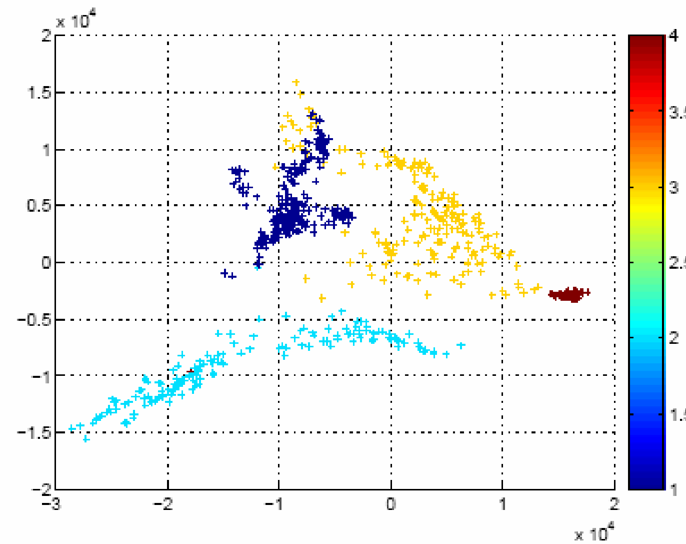






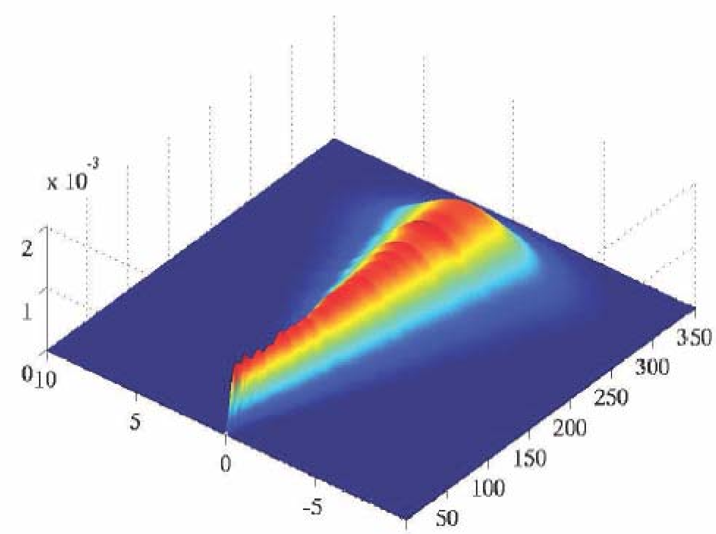
Example External Data Source: Hyperspectral Imagery

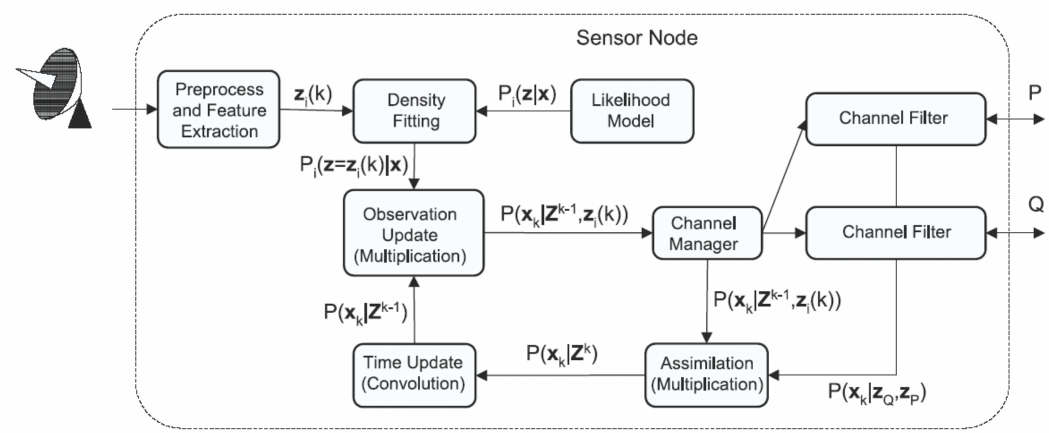




Feature-Based Tracking

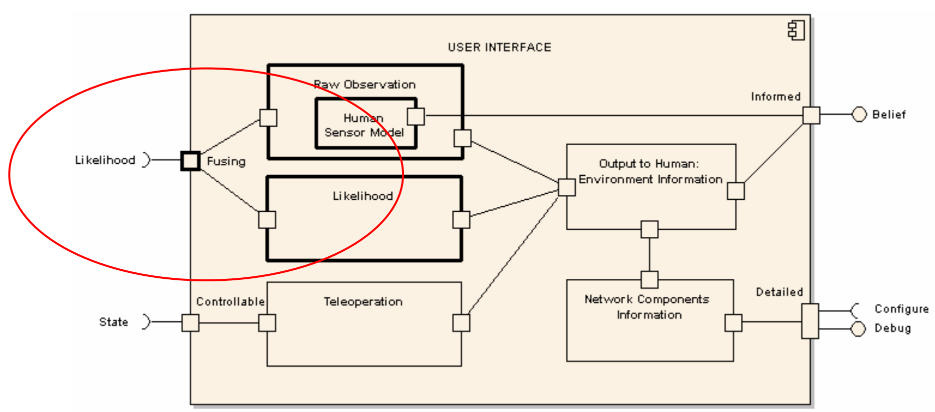
- General probability models:
  - Non-Gaussian location
  - Feature properties
  - Target IDs

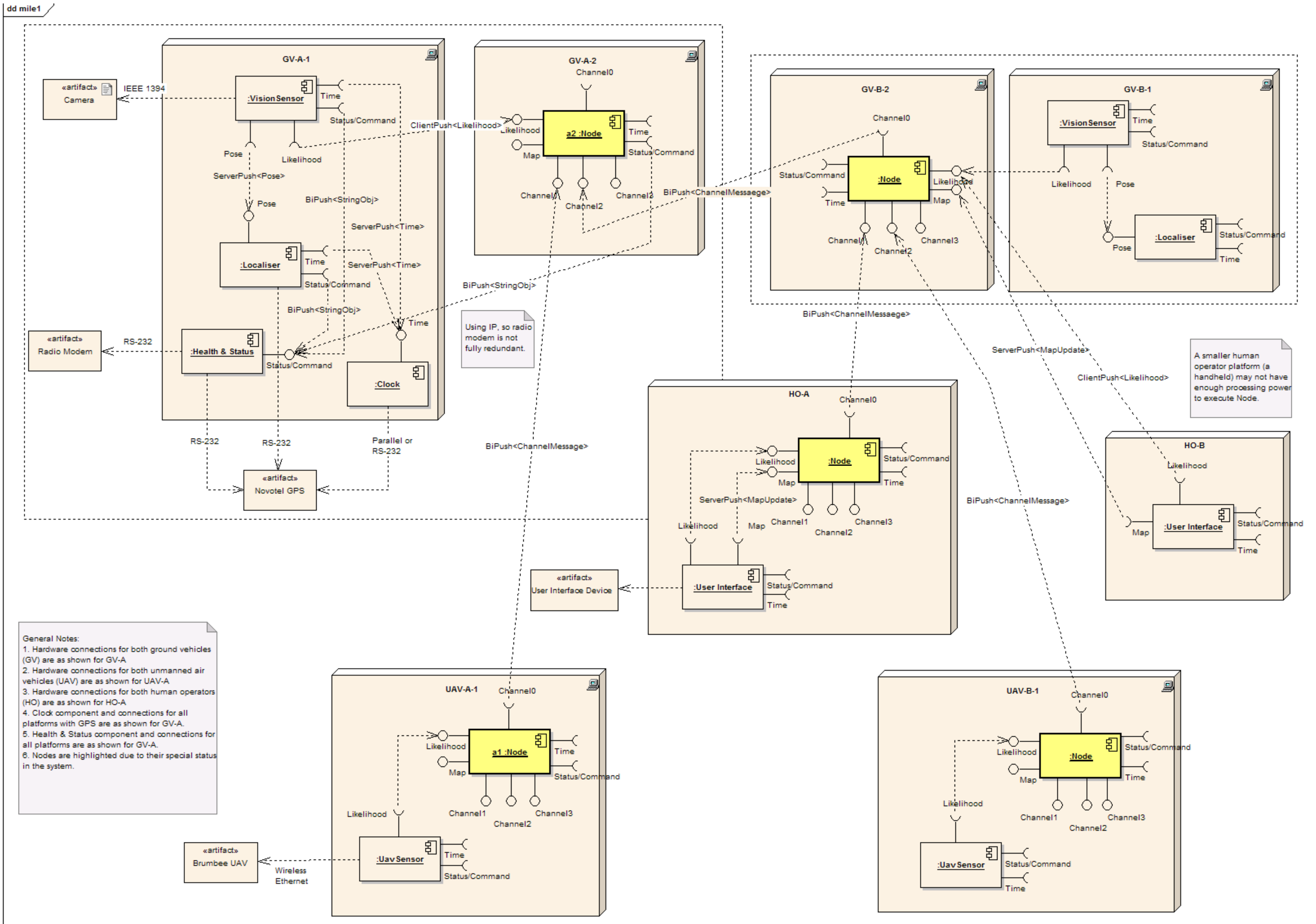




System Configuration and Design

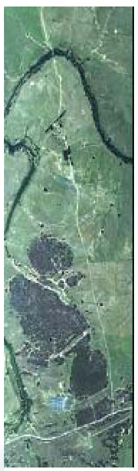
- Each module
  - Presents a likelihood
  - Generates a posterior
  - Computes a mutual information wrt a prior
- Mutual information in network determines
  - Who does what
  - Who talks to who
- Network properties
  - Survivable
  - Scalable

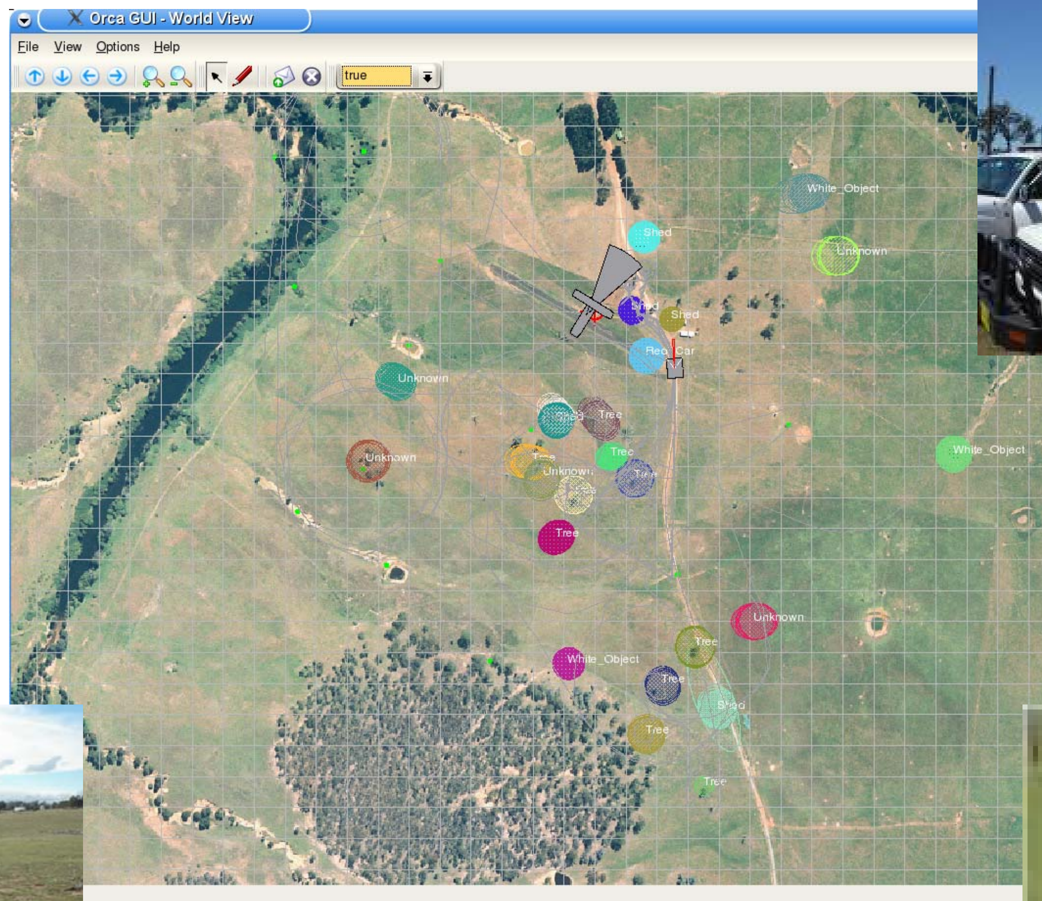


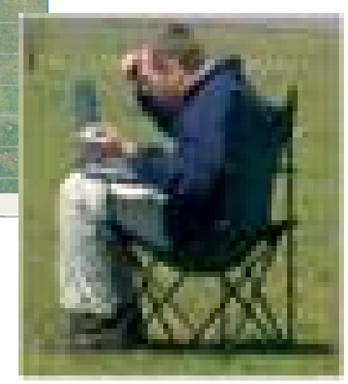


ORCA System Configuration File

Mission System Implementation

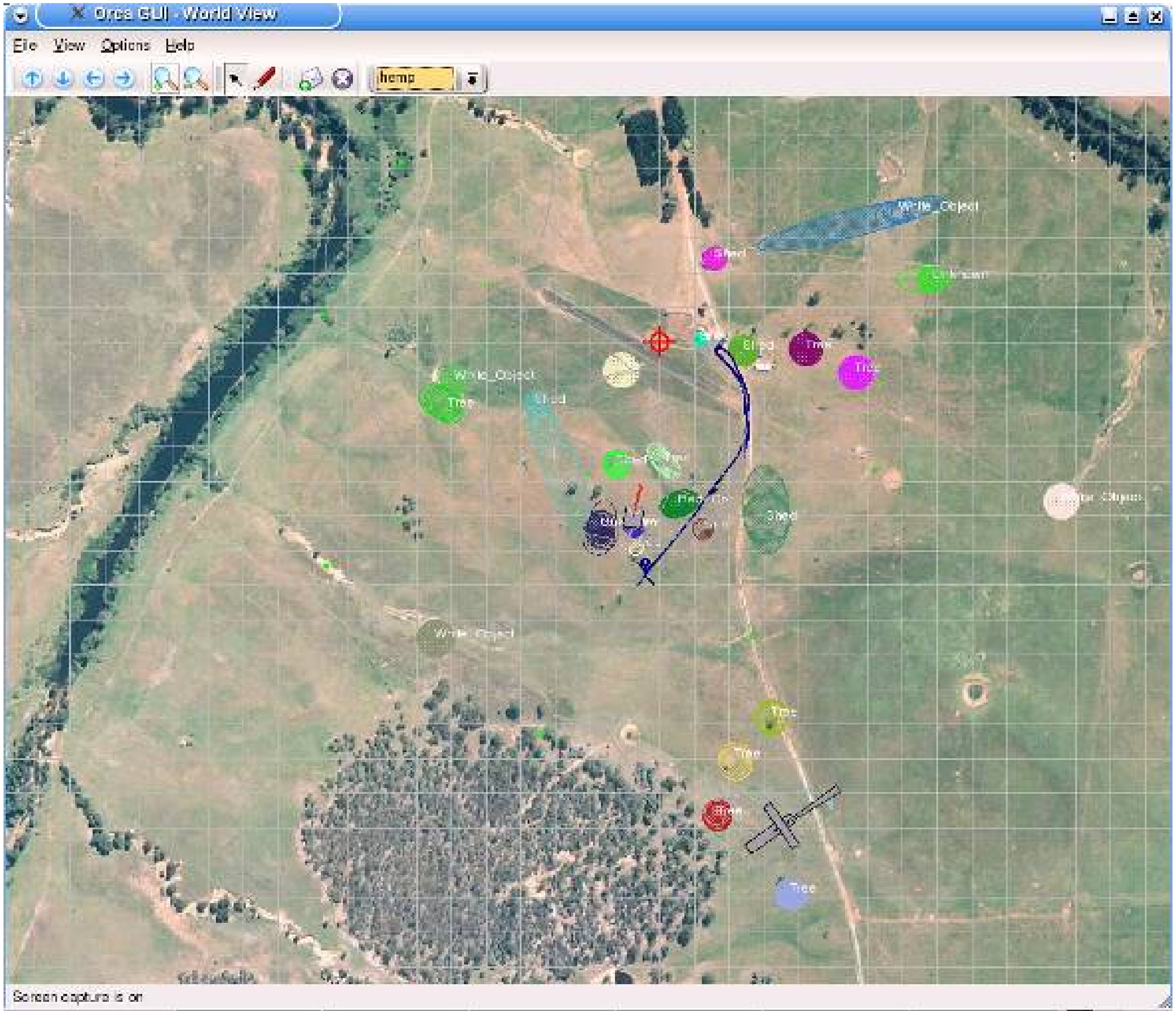






System Video

ANSER II System Demonstration

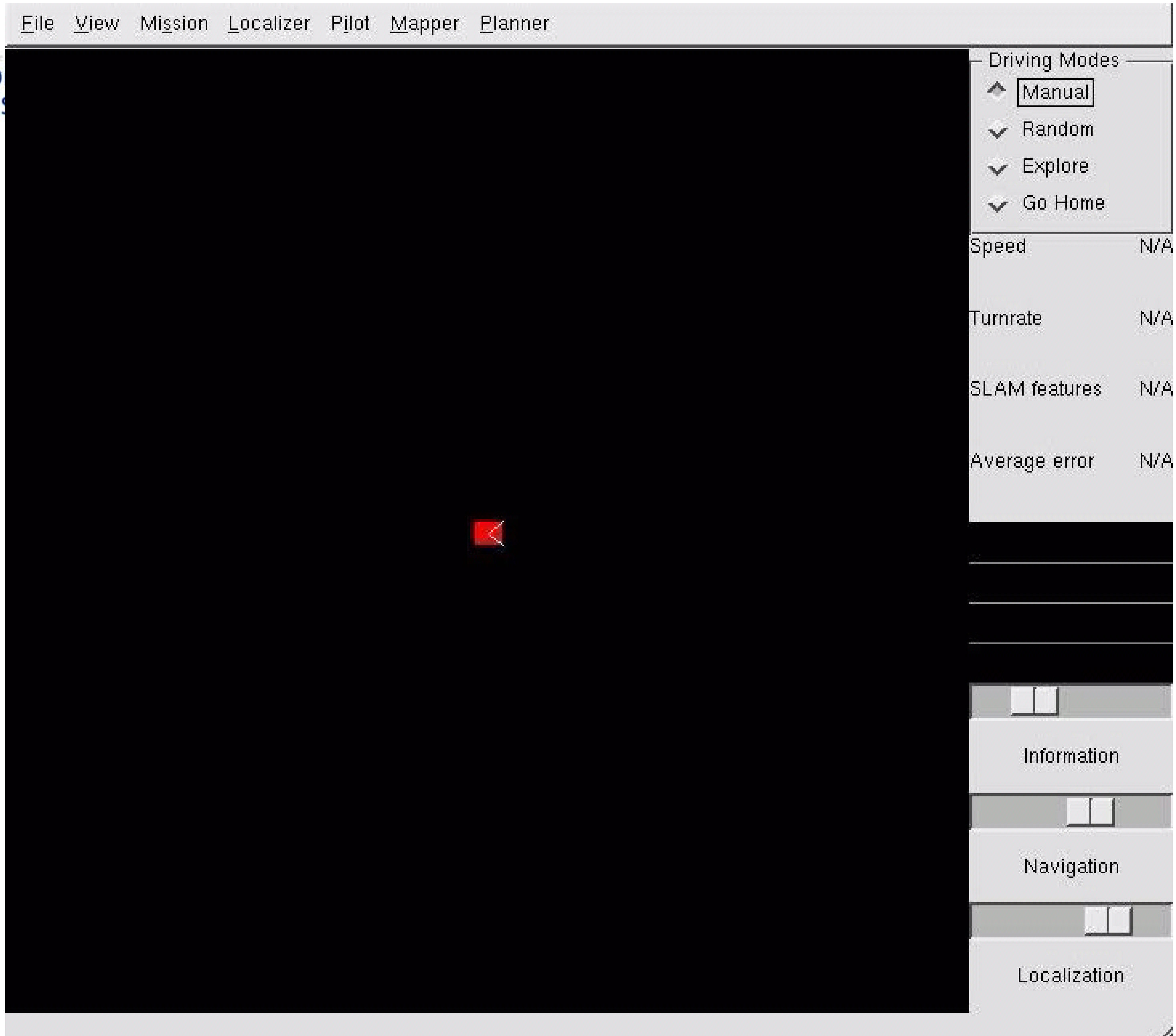


ANSER II Conclusions

- Fusion
  - General probabilistic models can be effectively decentralised
  - Modular, scalable, heterogeneous systems
  - Network management
- Systems design
  - Quantitative metrics for information-gathering systems
  - A priori and context dependent performance prediction
- This is a limited class of systems

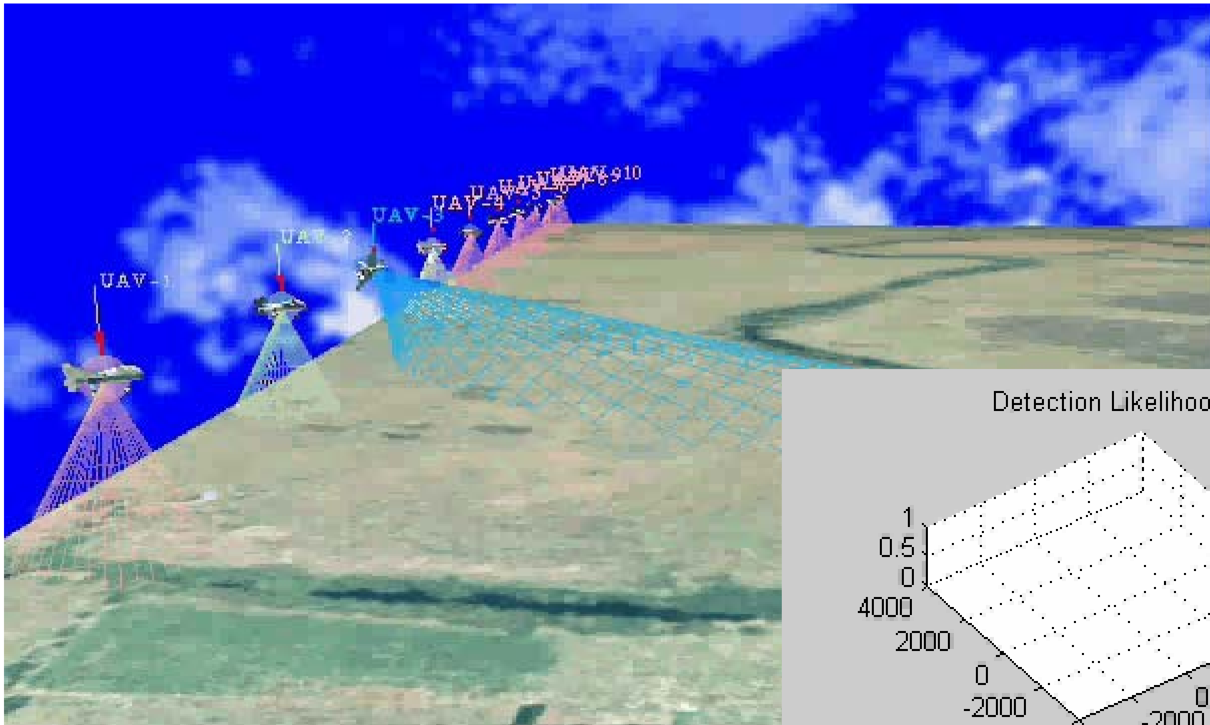
Extending the Paradigm

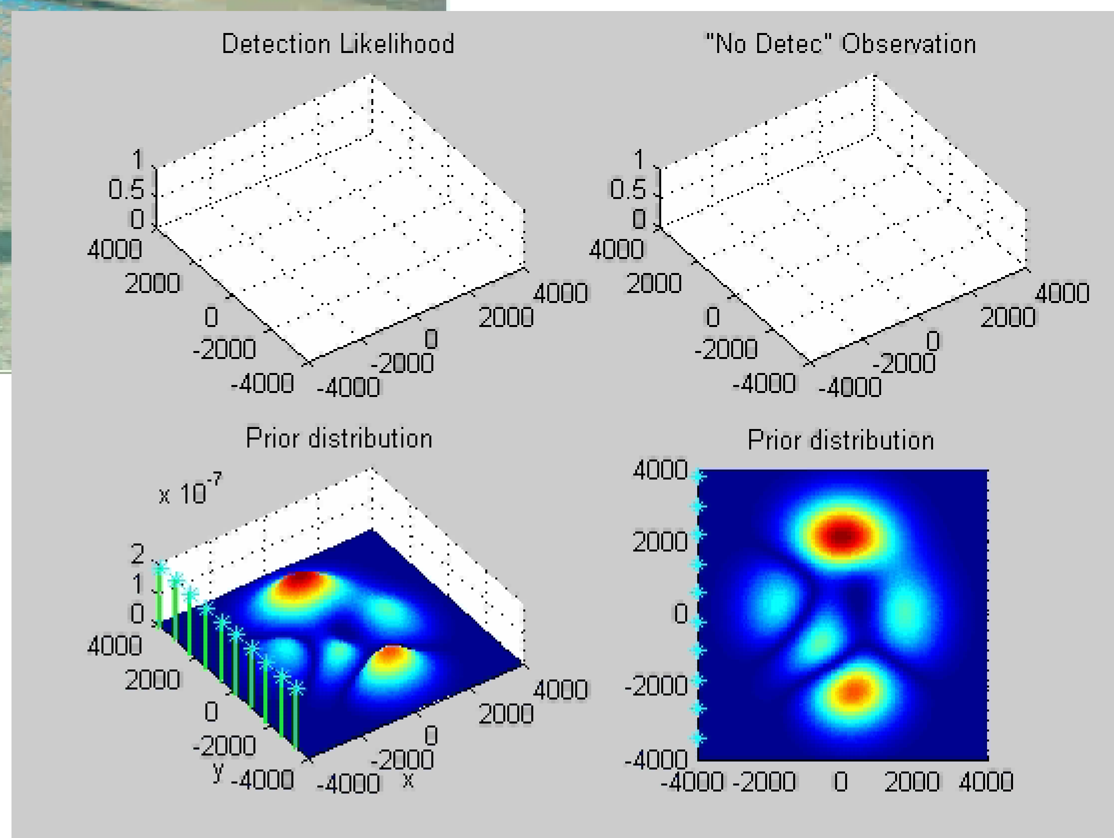
- Information maximisation control:
  - Decentralised structure
  - Scalable and system-robust
- Other information-maximising control
  - Resource use (platform, communications)
  - Target cuing, hand-off, etc
  - Search
  - Exploration


File View Mission Localizer Pilot Mapper Planner
Driving Modes
Manual
Random
Explore
Go Home
Speed N/A
Turnrate N/A
SLAM features N/A
Average error N/A
Information
Navigation
Localization

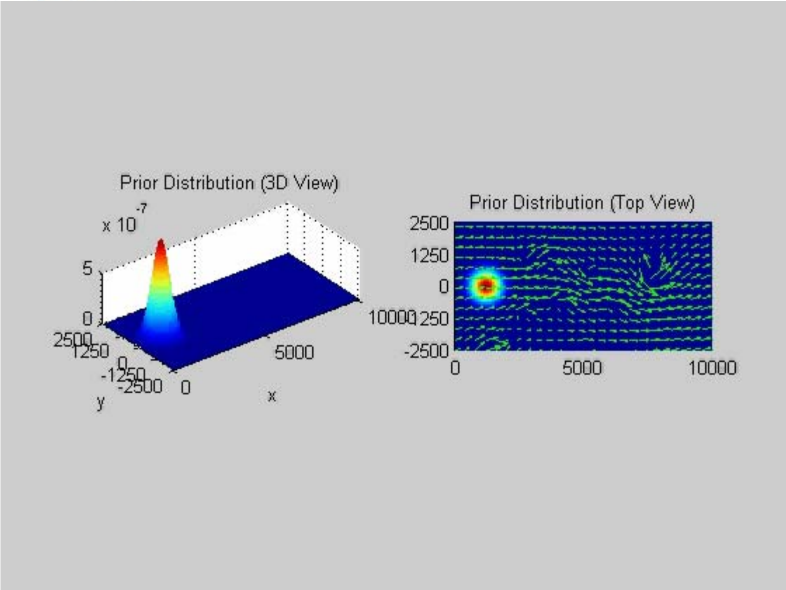
Multi-UAV Simple Search

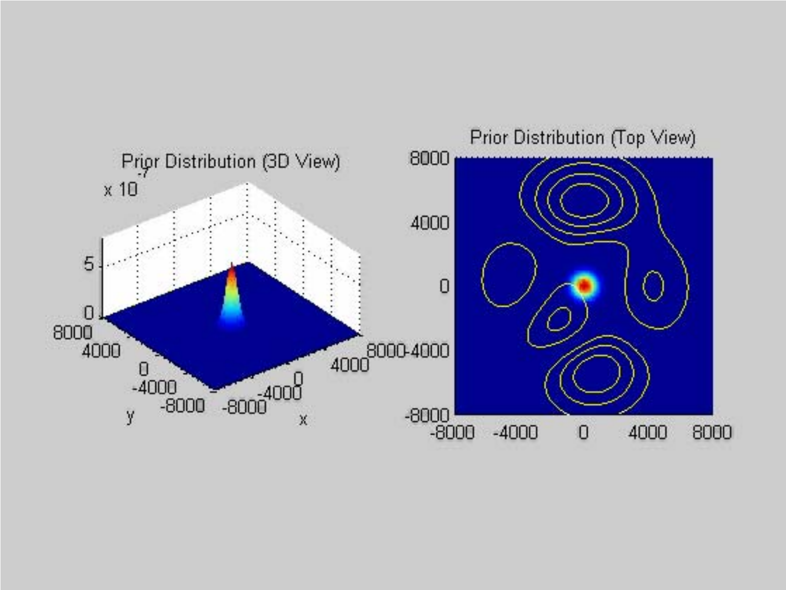
AFOSR/AOARD

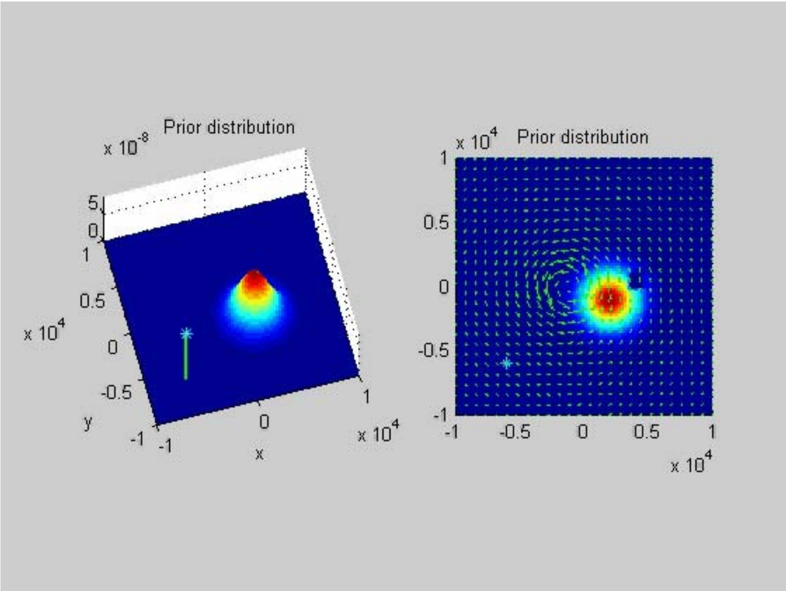


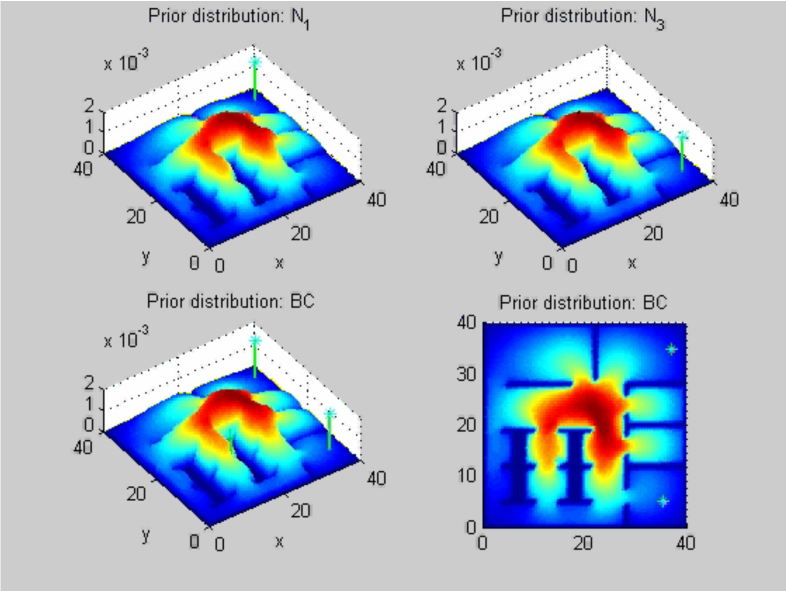


Exploiting Domain Knowledge: Dynamic, soft and hard constraints









ARC Centre of Excellence for Autonomous Systems

Multi-Univ UAV, Multi-Objective Control

- **AFRL WP AFB** Vehicles Directorate and AOARD
- **Objectives:**
  - A general information framework for cooperative control
  - On-line decentralised controllers for networks

- **Exploration**

$$J_i^{(expl)} = \int_0^T [\omega_i \delta_i(t)(i_i(t) - i_{\max}(t)) + (\omega_i - 1)\|\dot{\mathbf{u}}_i(t)\|]dt$$

- **Search**

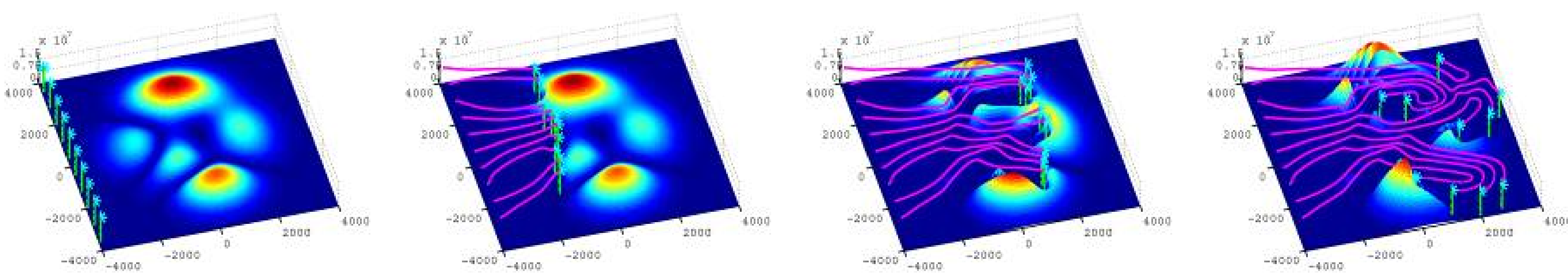
$$J_i^{(search)} = \int_0^T f(t)dt$$

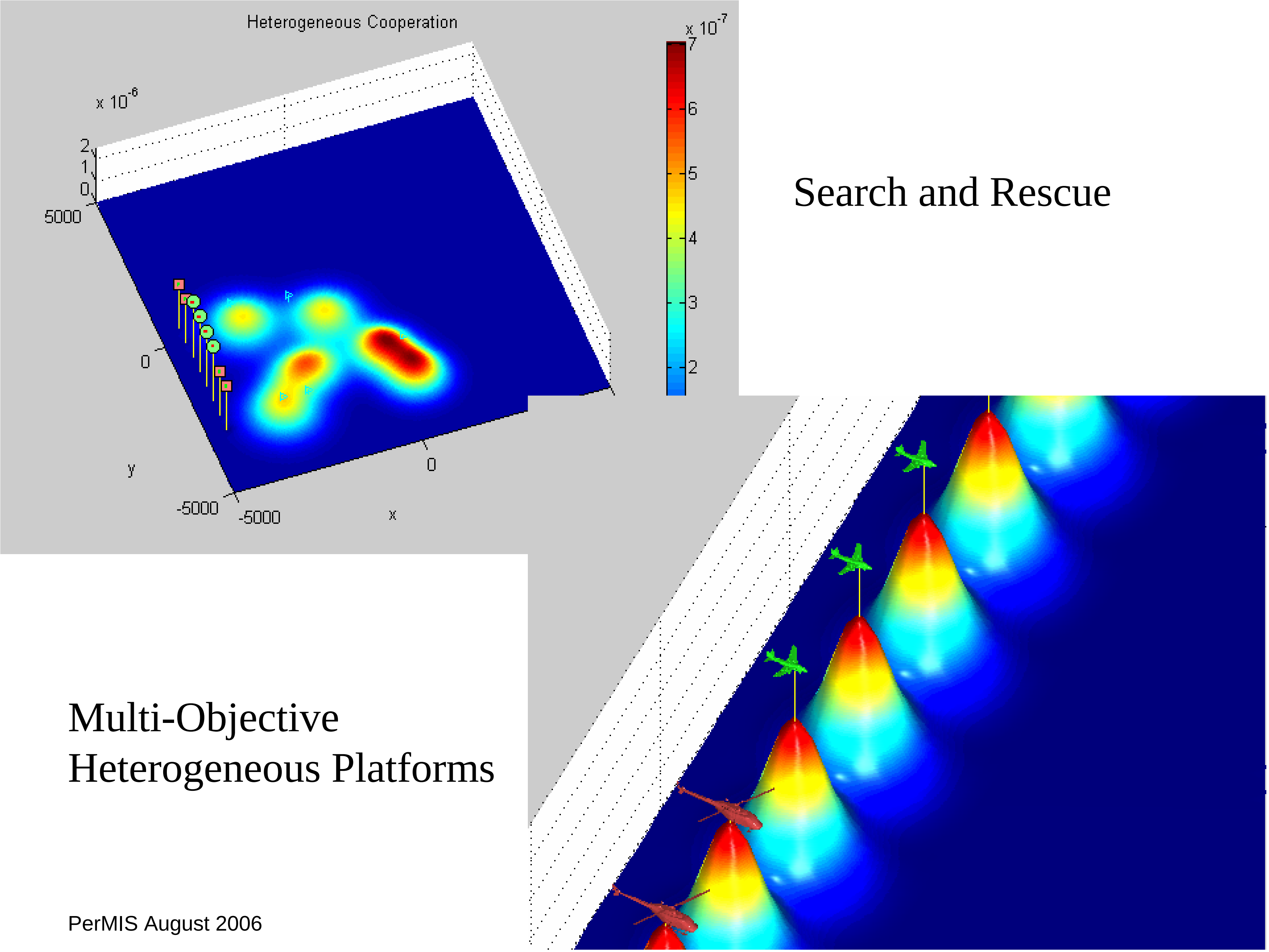
- **Tracking**

$$J_i^{(track)} = m\int_0^T \dot{v}(t)dt$$

- **Engagement**

$$J_i^{(engage)} = T$$

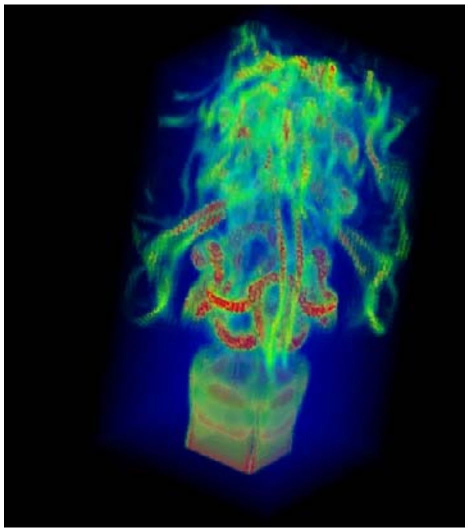




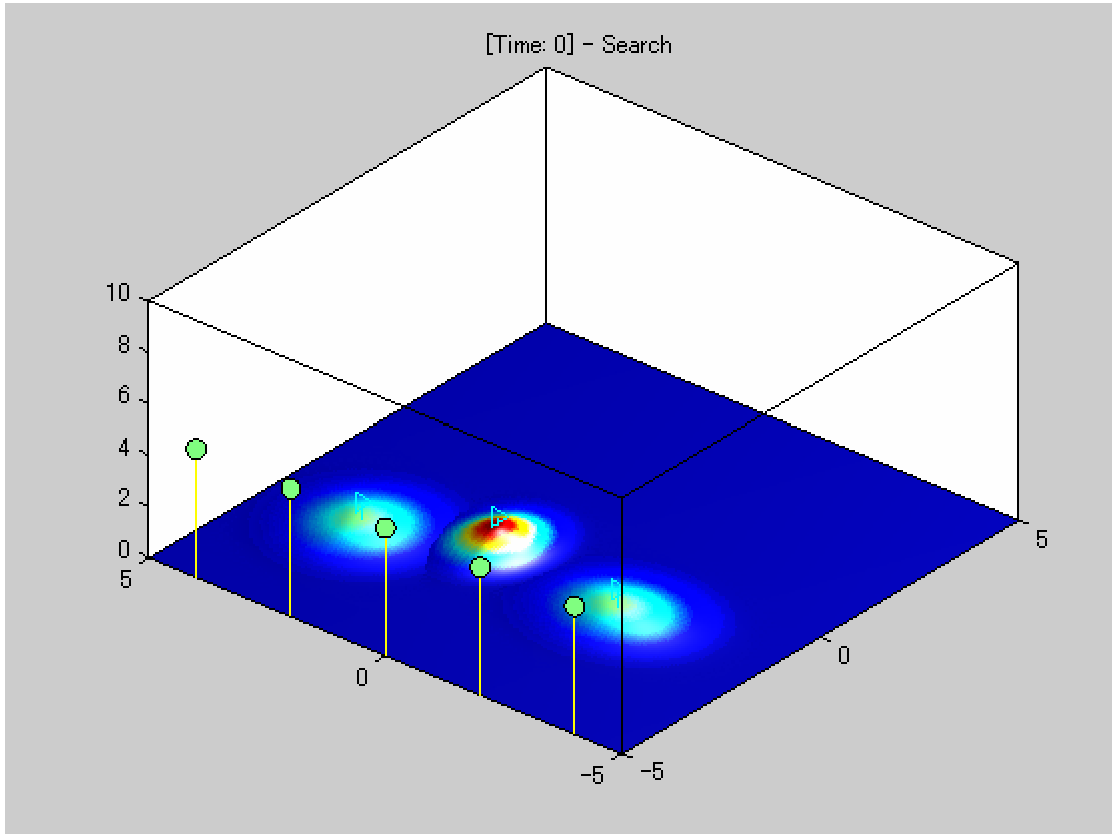
Search and Rescue

Multi-Objective
Heterogeneous Platforms

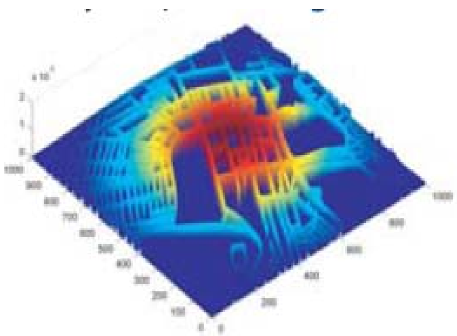
Cooperative plume-source localisation



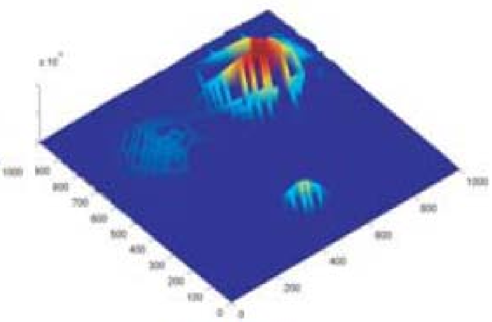
Putting the “physics” in the network



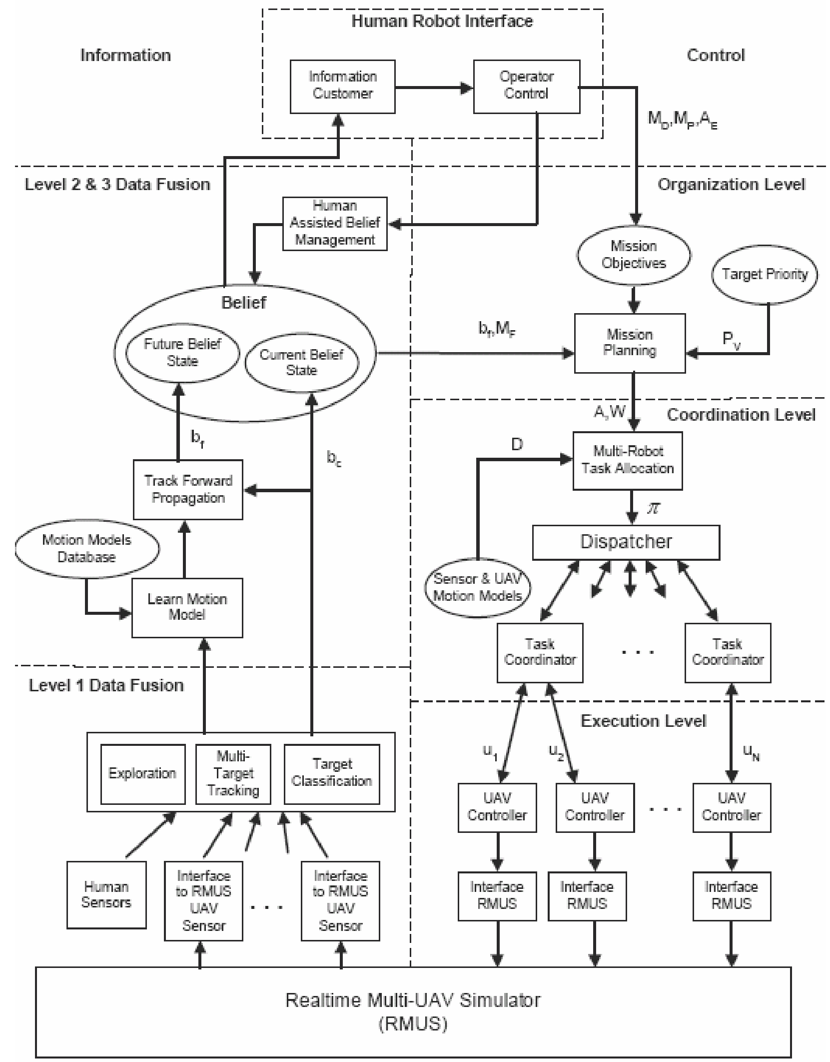
Human UAV Cooperation

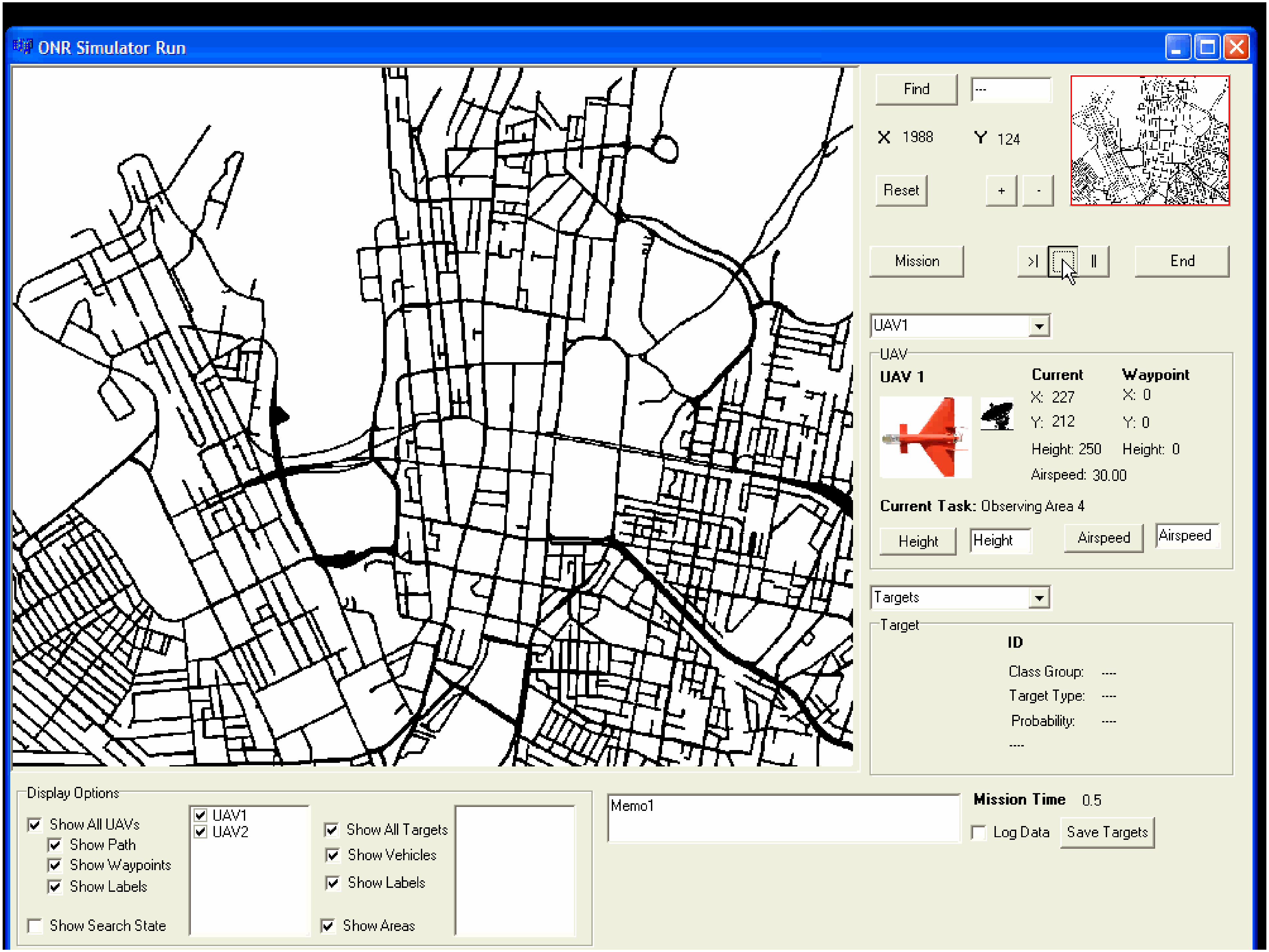


Probable locations of an object



Utility Map




ONR Simulator Run
Find

X 1988
Y 124
Reset
+
-
Mission
>|
||
End
UAV1
UAV
UAV 1
Current
Waypoint
X: 227
Y: 212
Height: 250
Airspeed: 30.00
X: 0
Y: 0
Height: 0
Current Task: Observing Area 4
Height
Height
Airspeed
Airspeed
Targets
Target
ID
Class Group: ----
Target Type: ----
Probability: ----

Display Options
Show All UAVs
Show Path
Show Waypoints
Show Labels
Show Search State
UAV1
UAV2
Show All Targets
Show Vehicles
Show Labels
Show Areas
Memo1
Mission Time 0.5
Log Data
Save Targets

Conclusions

- Information
  - Mathematical basis for network fusion
  - An a priori measure of performance
  - An integrated idea of context
  - A system design measure
- Future directions
  - Automate system design process
  - Extend complexity of information-gathering
  - Non-information problems and pay-off seperability

Questions ?