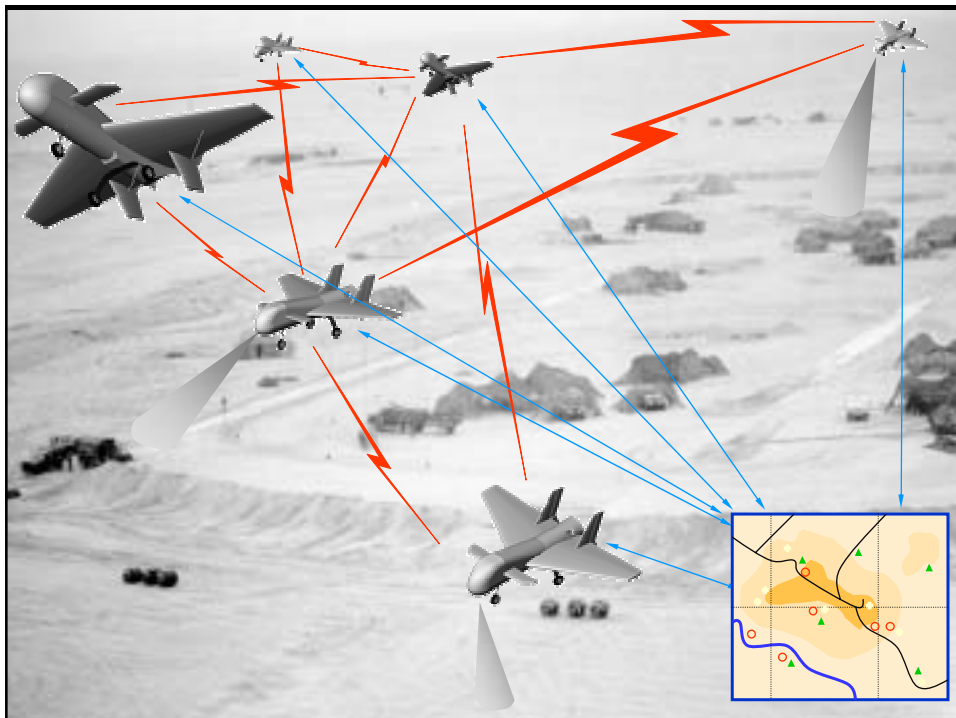
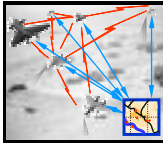


SLAM IN AIR VEHICLE APPLICATIONS

Salah Sukkariéh
salah@acfr.usyd.edu.au

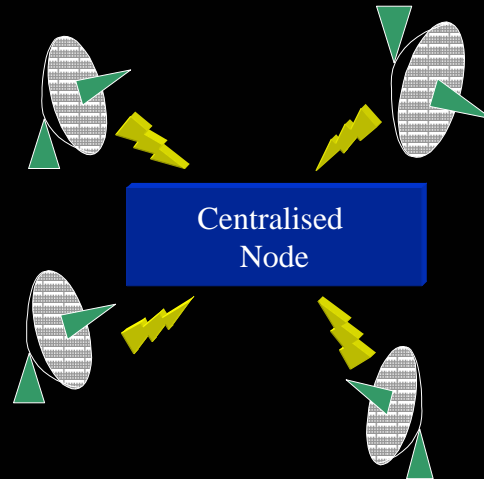
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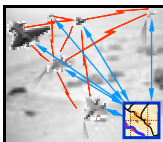
Centralised Data Fusion

- Excessive Communication Bandwidth
- Excessive Computational Expense
- Low Level of Integrity



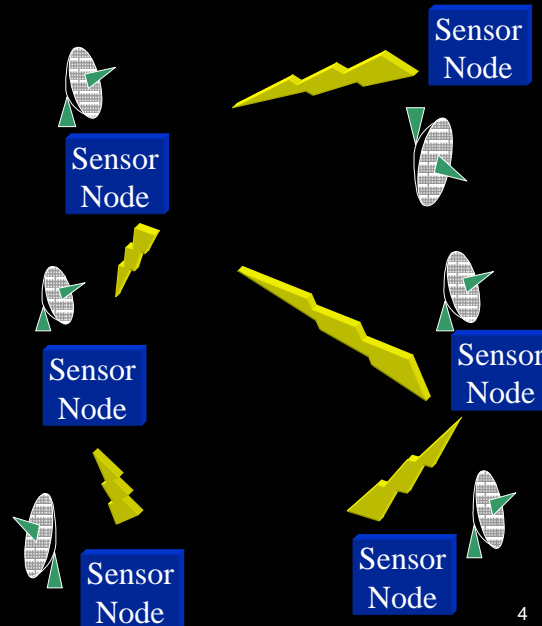
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3



Decentralised Data Fusion

- Increased Integrity
- Reduction in computation and communication expense
- Wider coverage area
- Results are obtained quicker



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4

Physical System

5

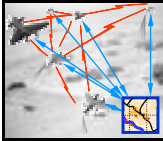


Flight Platforms

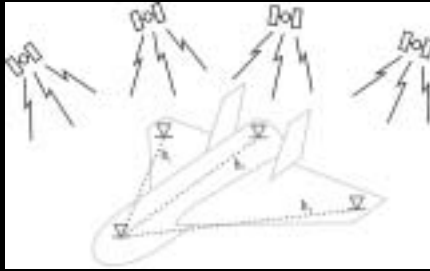


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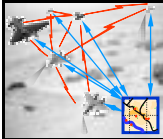


INS/GPS

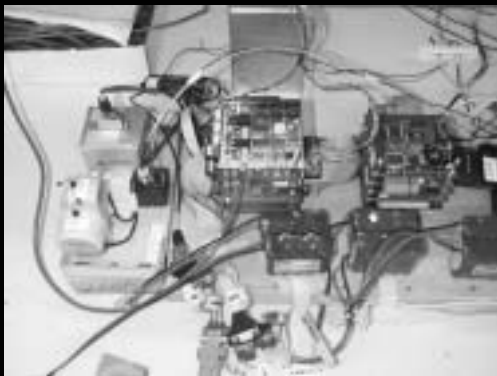


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Vision + Laser/Vision Sensors



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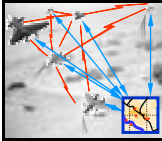
8

Radar Sensor

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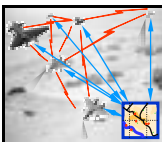
Simultaneous Localisation and Map Building

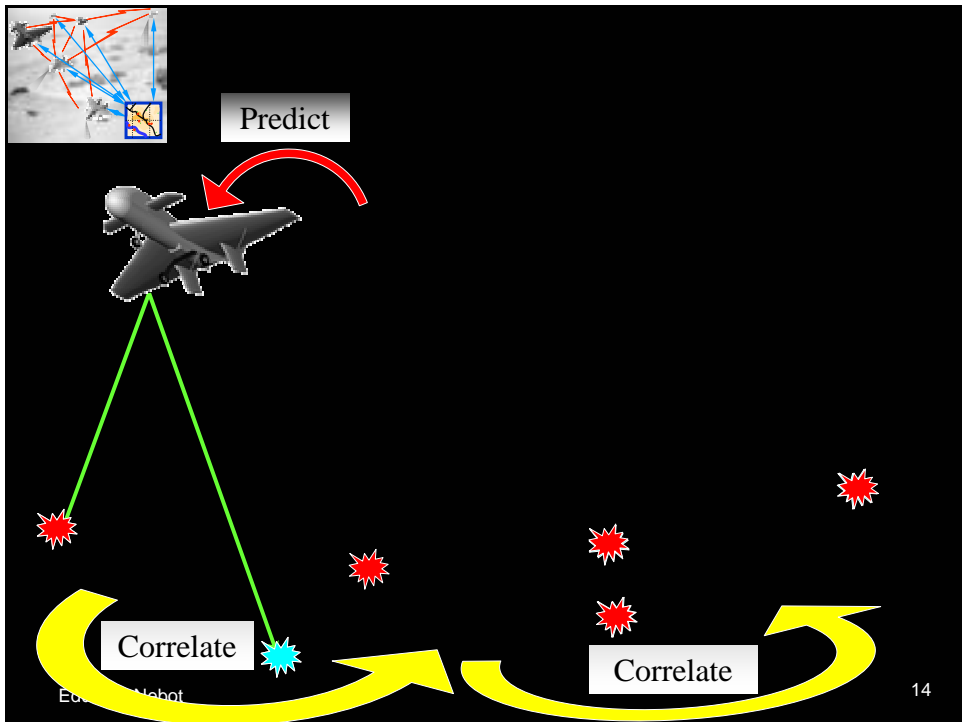
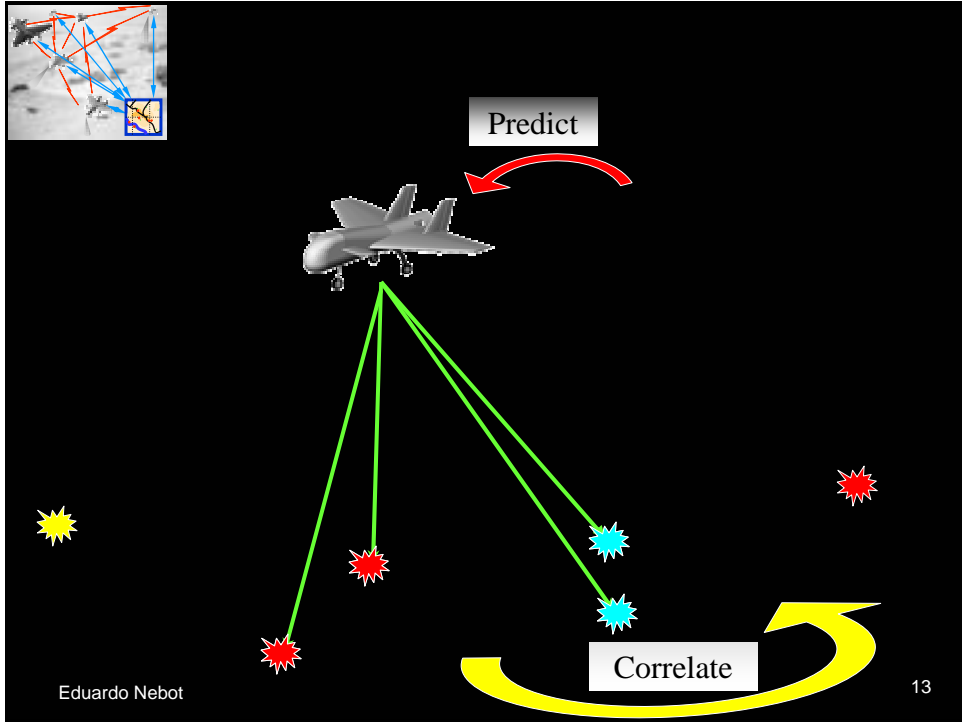
10

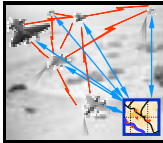


SLAM

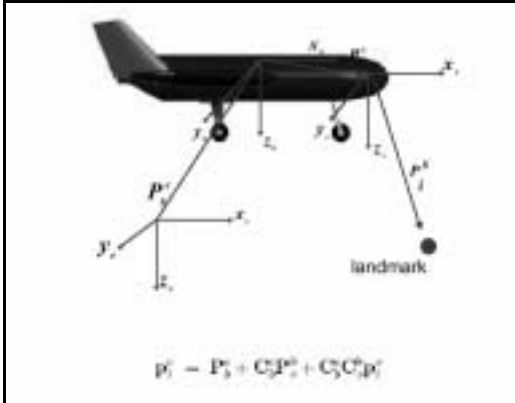
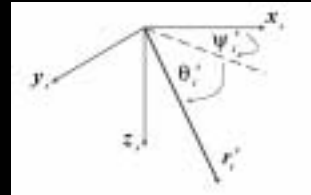
- Highly non-linear
 - 6DoF Estimation
 - Information is only $2^{1/2}D$
 - Observability Issues
-
- Standard Cartesian
 - Raw Fusion





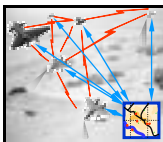


SLAM



$$\begin{aligned} \dot{P}_0^c &= V_0^c \\ \dot{V}_0^c &= C_0^c f_0 \\ \dot{\phi} &= \omega_z + (\omega_y \sin \phi + \omega_x \cos \phi) \tan \theta \\ \dot{\theta} &= \omega_y \cos \phi - \omega_x \sin \phi \\ \dot{\psi} &= \frac{\omega_y \sin \phi + \omega_x \cos \phi}{\cos \theta} \end{aligned}$$

$$x(k) = [x_0^T(k) \ p_1^T(k) \ p_2^T(k) \ \dots \ p_N^T(k)]^T$$

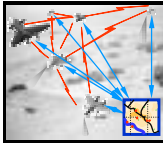


SLAM – Error Analysis

$$\delta p_1^c = \tilde{p}_1^c - p_1^c$$

$$\begin{aligned} \delta \dot{P}_0^c &= \delta V_0^c \\ \delta \dot{V}_0^c &= [C_0^c f_0 \times] \delta \psi_0^c + C_0^c \delta f_0 \\ \delta \dot{\psi}_0^c &= -C_0^c \delta \omega_z \end{aligned}$$

$$\delta p_1^c = \delta P_0^c + C_0^c \delta p_0^b + [C_0^c \tilde{P}_0^b \times] \delta \psi_0^c + C_0^c C_0^b \delta p_1^l + [C_0^c C_0^b \tilde{P}_1^l \times] (\delta \psi_0^c + \delta \theta_1^b)$$



INS/SLAM - Observation

- Non-linear observation model
- Observation Model
 - ◆ In Cartesian coordinate

$$z(t) = h(x(t)) + v(t)$$

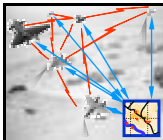
$$z_{\text{cartesian}} \equiv [x \quad y \quad z]^T = p_{ts}^s \\ = C_s^{bT} C_b^{nT} [p_{t_i}^n - p_v^n - C_b^n p_{sb}^b]$$

- ◆ In Spherical coordinate

$$z_{\text{spherical}} \equiv [r \quad \psi \quad \theta]^T = g_1(p_{ts}^s) \\ = \begin{bmatrix} \sqrt{x^2 + y^2 + z^2} \\ \tan^{-1}(y/x) \\ \tan^{-1}(z/\sqrt{x^2 + y^2}) \end{bmatrix}$$

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17



INS/SLAM - Observation

- Jacobian In Cartesian coordinates

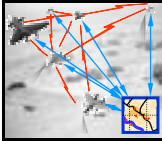
$$H_{\text{cartesian}} = \nabla_x h \\ = \begin{bmatrix} -C_s^{bT} C_b^{nT} & 0_{3 \times 3} & \frac{\partial p_{ts}^s}{\partial \psi} & \dots & (C_s^{bT} C_b^{nT})^i & \dots \end{bmatrix}$$

- Jacobian In Spherical coordinates

$$H_{\text{spherical}} = \nabla_x h = \nabla g_1 \nabla g_2 \\ = \begin{bmatrix} \frac{x}{r} & \frac{y}{r} & \frac{z}{r} \\ \frac{-y}{x^2+y^2} & \frac{x}{x^2+y^2} & 0 \\ \frac{-x}{r^2\sqrt{x^2+y^2}} & \frac{-y}{r^2\sqrt{x^2+y^2}} & \frac{\sqrt{x^2+y^2}}{r^2} \end{bmatrix} \begin{bmatrix} -C_s^{bT} C_b^{nT} & 0_{3 \times 3} & \frac{\partial p_{ts}^s}{\partial \psi} & \dots & (C_s^{bT} C_b^{nT})^i & \dots \end{bmatrix}$$

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18



INS/SLAM - EKF

- EKF formulation

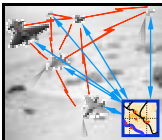
$$\begin{aligned} x_{k+1} &= f(x_k, u_{k+1}) + w_k \\ z_k &= h(x_k) + v_k \end{aligned}$$

- Prediction

$$\begin{aligned} x_{k+1|k} &= f(x_k, u_{k+1}) \\ P_{k+1|k} &= \nabla_x f_k P_{k|k} \nabla_x f_k^T + \nabla_u f_k U_k \nabla_u f_k^T + Q_k \end{aligned}$$

- Update

$$\begin{aligned} v_k &= z_k - h(x_k) \\ S_k &= \nabla_x h P_{k+1|k} \nabla_x h^T + R_k \\ W_k &= P_{k+1|k} \nabla_x h^T S_k^{-1} \\ x_{k+1|k+1} &= x_{k+1|k} + W_k v_k \\ P_{k+1|k+1} &= P_{k+1|k} - W_k S_k W_k^T \end{aligned}$$



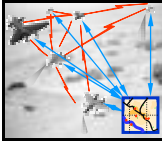
INS/SLAM - EKF

- Data association

$$v_k^T S_k^{-1} v_k \leq d_{\min}$$

- New feature Augmentation

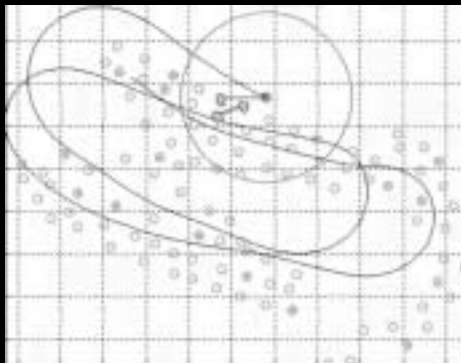
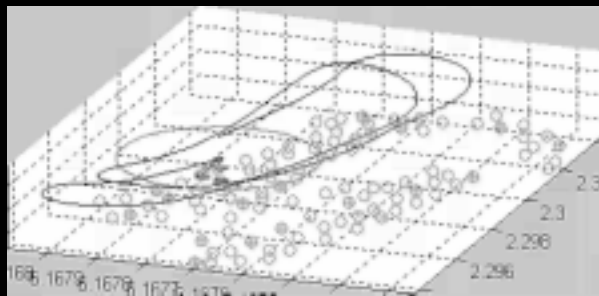
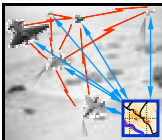
$$\begin{aligned} x_{\text{new}} &= \begin{bmatrix} x_k \\ g(x_k, z_k) \end{bmatrix} \\ P_{\text{new}} &= \begin{bmatrix} I & 0 \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial z} \end{bmatrix} \begin{bmatrix} P_k & 0 \\ 0 & R_k \end{bmatrix} \begin{bmatrix} I & 0 \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial z} \end{bmatrix}^T \end{aligned}$$

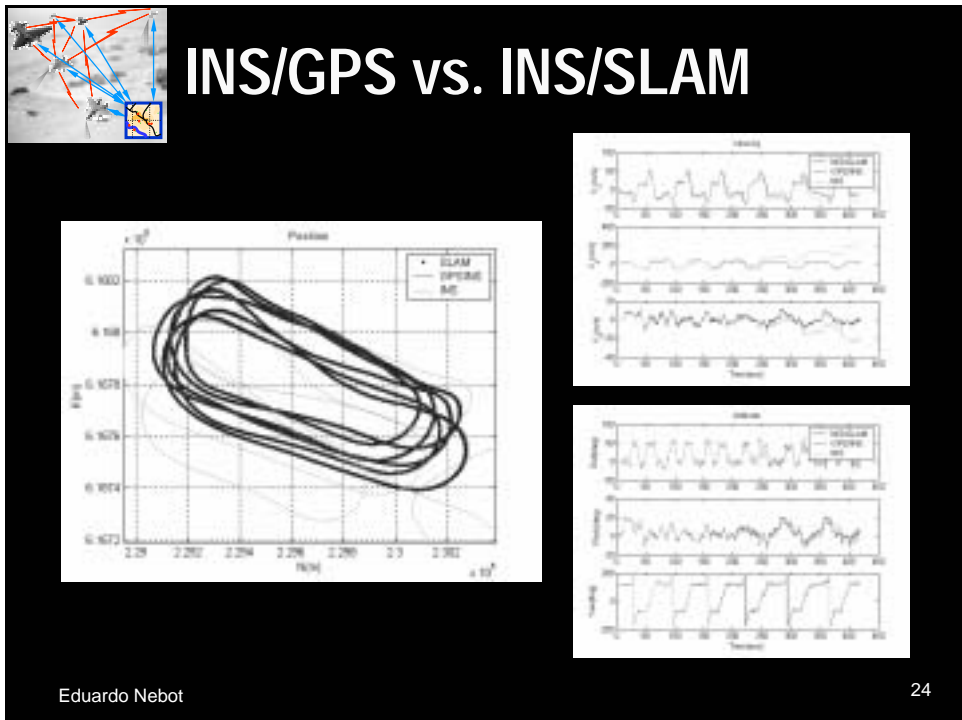
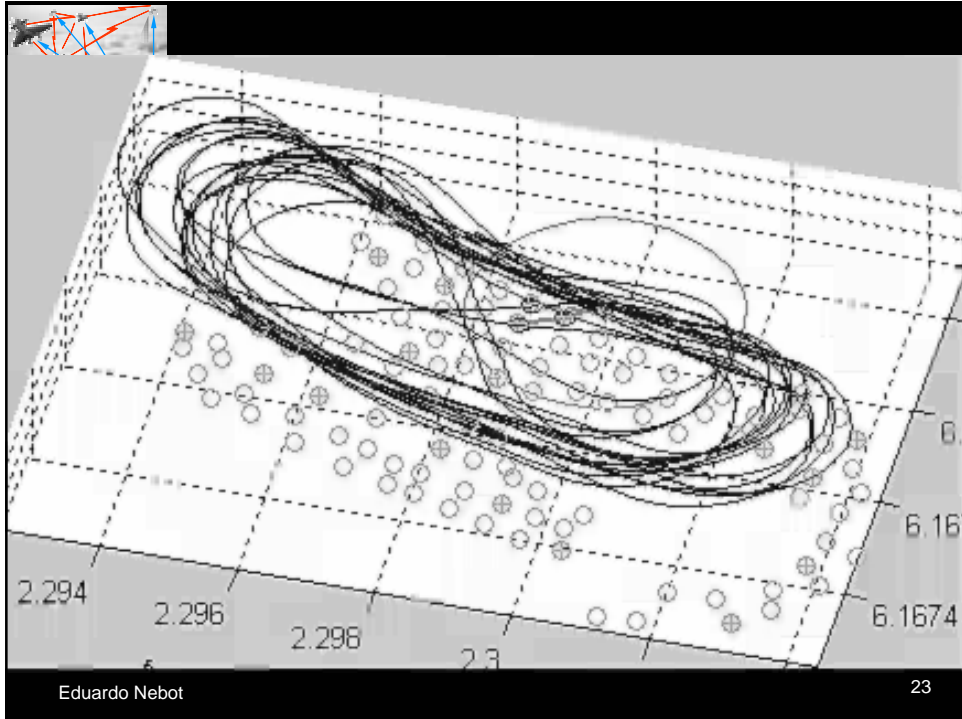


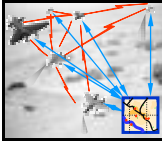
INS/SLAM

- Observation in Spherical vs. Cartesian coordinate

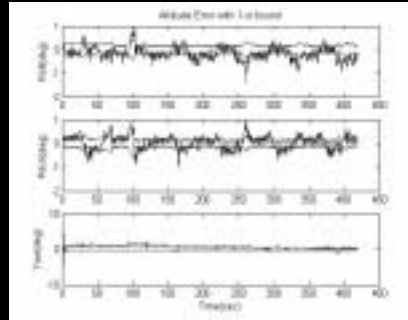
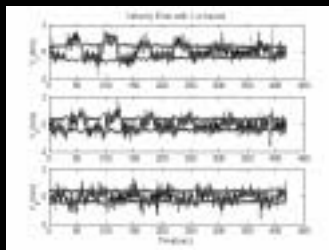
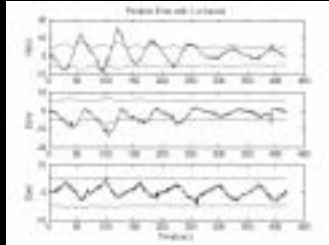
Spherical	Cartesian
Non-linear observation model	Linear observation model
Un-correlated observation (range,bearing,elevation)	Correlated observation (x,y,z)
Suitable for single-platform tracking	Suitable for multi-platform tracking





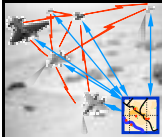


Difference between INS/GPS and INS/SLAM



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25

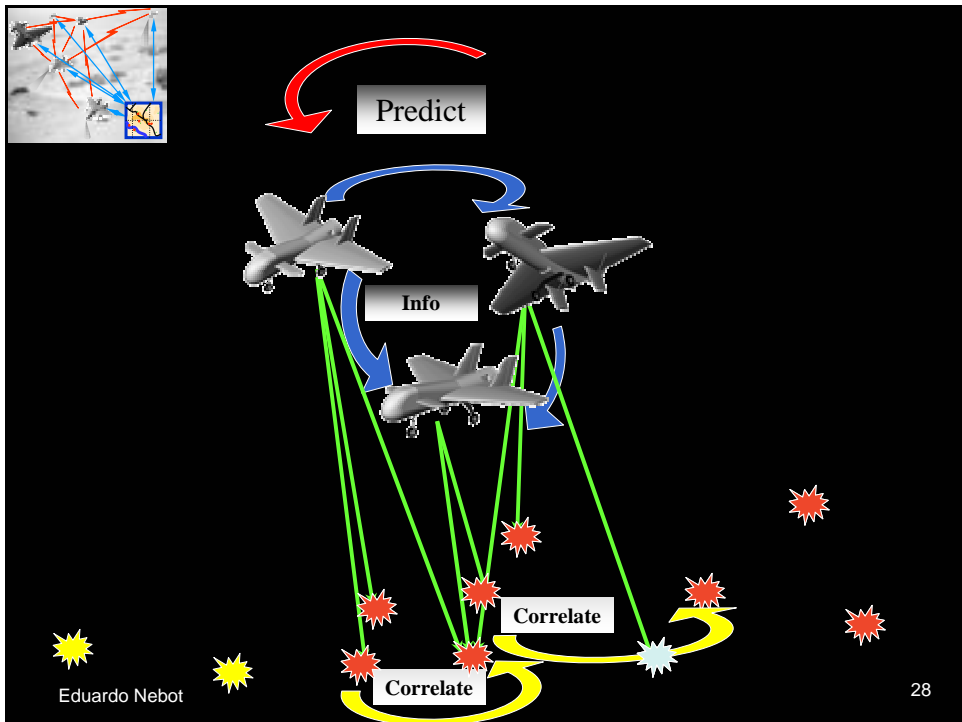
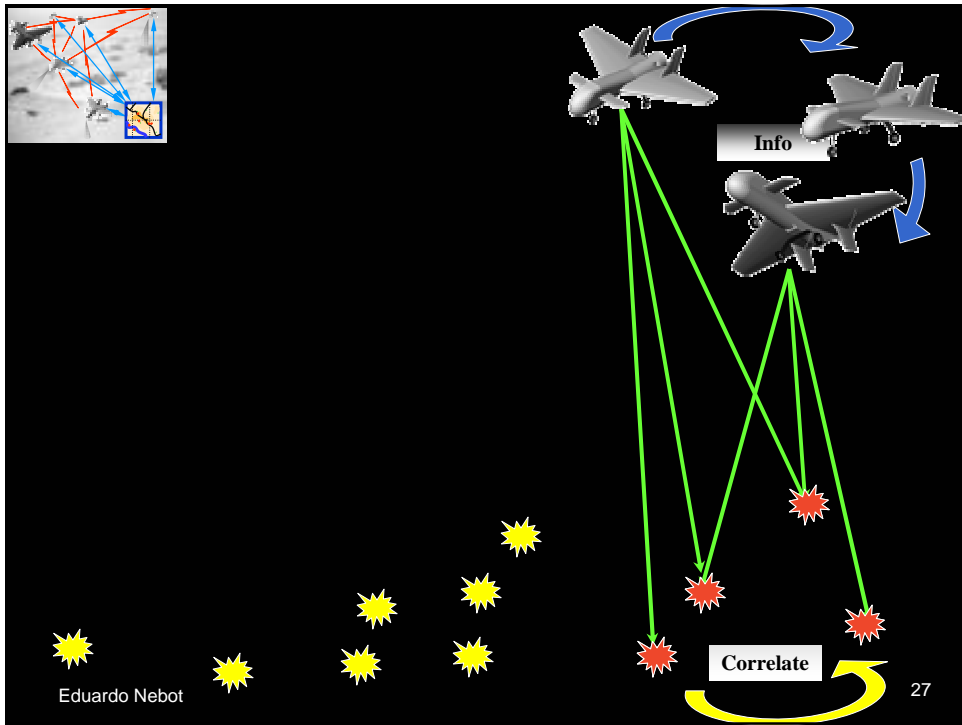


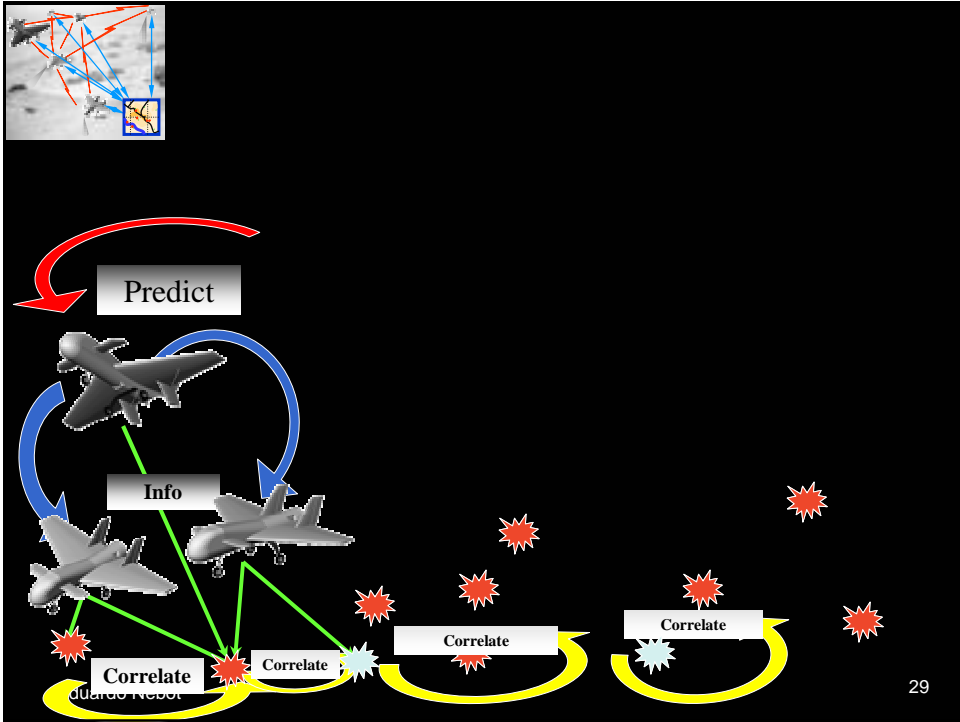
DDF SLAM

- Sharing of Map Information
- Mixture of State and Information forms

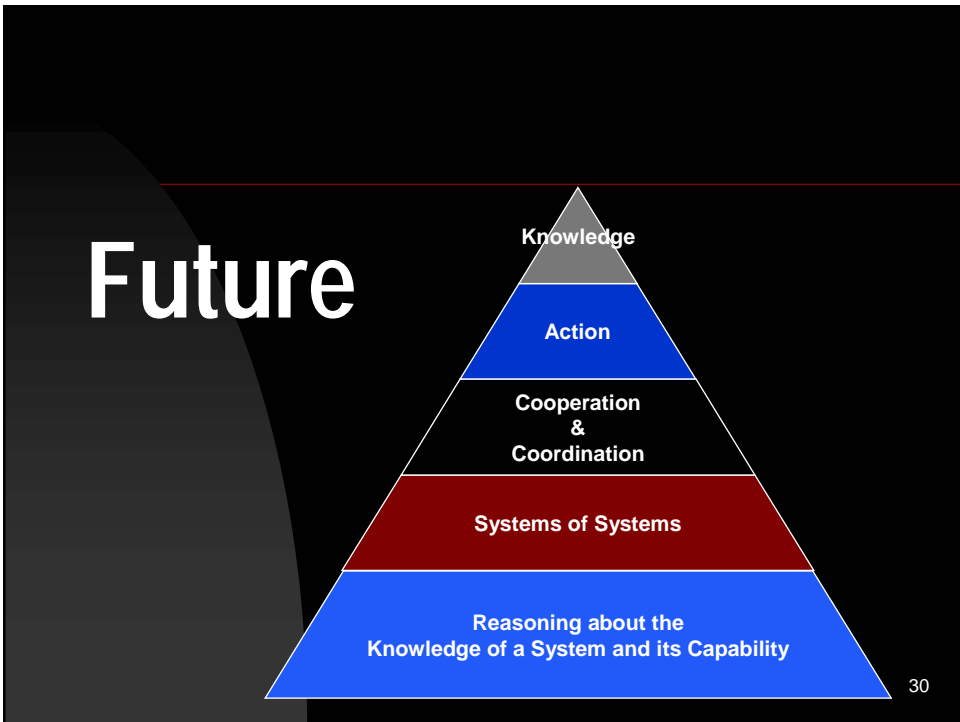
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26

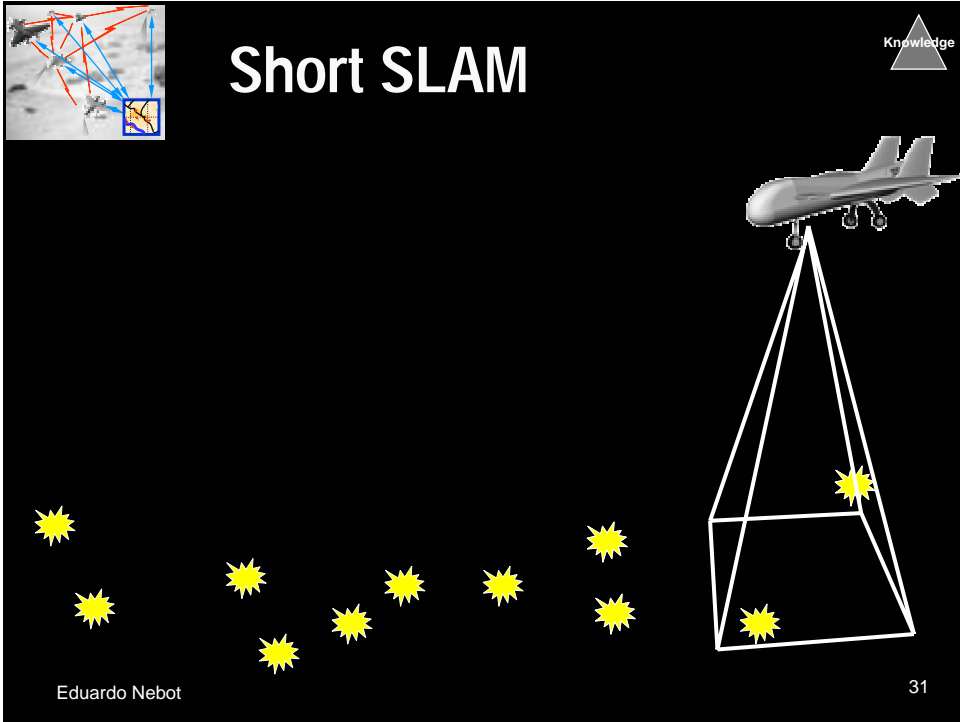




29



30

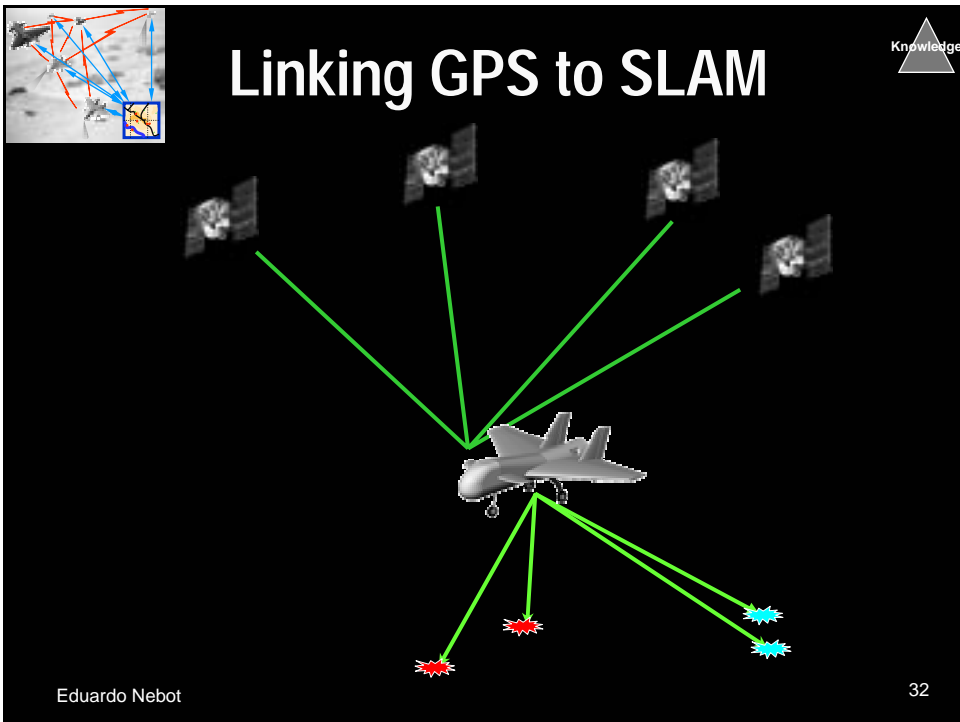


Short SLAM

Knowledge

Eduardo Nebot 31

The diagram illustrates the Short SLAM process. It features a small inset in the top-left corner showing a robot's path with red and blue lines. The main scene shows a grey airplane at the top right, with white lines forming a frustum that projects onto a black plane below. Several yellow starburst markers are scattered on the plane, representing feature points. A grey triangle labeled 'Knowledge' is in the top right corner. The name 'Eduardo Nebot' and the number '31' are in the bottom left and right corners, respectively.

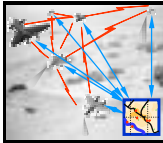


Linking GPS to SLAM

Knowledge

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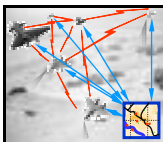
The diagram illustrates the process of linking GPS to SLAM. It features a small inset in the top-left corner showing a robot's path with red and blue lines. The main scene shows a grey airplane at the bottom center. Several green lines radiate from the airplane to various satellite icons (GPS) positioned around it. Below the airplane, there are red and cyan starburst markers. A grey triangle labeled 'Knowledge' is in the top right corner. The name 'Eduardo Nebot' and the number '32' are in the bottom left and right corners, respectively.



Autonomous SLAM

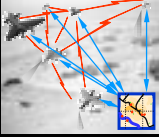


- Need to assure integrity of navigation system is exceptional in order to close the loop
- Decision Time
 - ◆ Exploration or Exploitation
 - ◆ Future Horizon
 - ◆ Hybrid Control




Non-Gaussian Fusion and Control

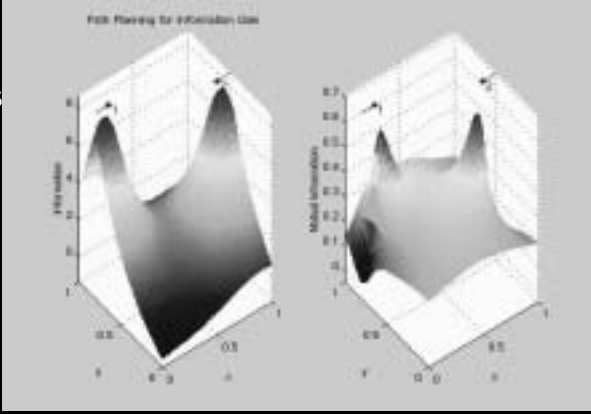




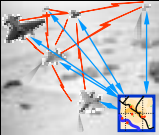
Cooperative Platform Trajectory Generation




- Mutual information gain
 - ◆ Expected information gain is communicated
 - ◆ Local knowledge of global information
- Trajectory control localised based on maximising global utility

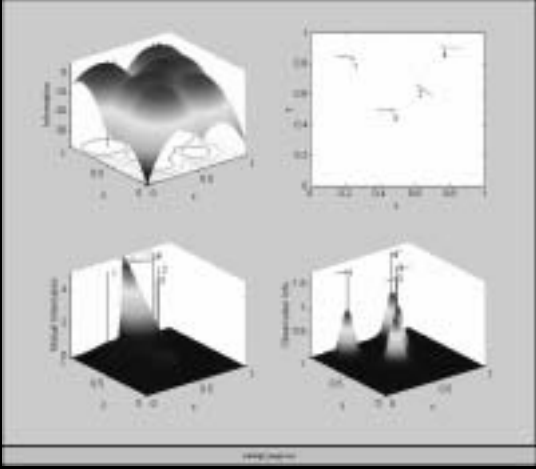


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Cooperative Platform Trajectory Generation





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Air-Ground DDF and DCC

Systems of Systems

The diagram illustrates the integration of various systems into a larger network. At the top left, a network graph shows nodes connected by red and blue lines. The central area contains several images: a tank, a fighter jet, a truck, a satellite, a commercial airplane, a cockpit, and a ground control station. Red arrows point from these images to a large bottom image showing a landscape with a radio tower. Yellow arrows point from the bottom image back to the satellite, tank, and ground control station images.

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