



Some Issues on Autonomous Vehicles Control Management

Mario Innocenti

Department of Electrical Systems and Automation
University of Pisa
Via Diotisalvi, 2 - 56126 Pisa, ITALY

Society of Automotive Engineers
Aerospace Control and Guidance Systems Committee
Meeting # 97, 1 - 3 March 2006



2 March, 2006



Outline



- Introduction
- Formation Flight
- Path and Task Assignment
- Vision - based Aids
- Conclusions



2 March, 2006





Introduction



- The research presented here was and/or is partially funded by :
 - MIUR - Italian Ministry of University
 - MBDA - Missile Systems Division, La Spezia Italy
 - EOARD - US European Office of Aerospace Research and Development
 - AFOSR , AFRL /VA, AFRL / MNA
 - European Community VI FP HYCON Project
- Cooperations:
 - West Virginia University
 - Ohio State University
 - UCLA
 - UC Berkeley
 - Middle Eastern Technical University, Turkey
- Locations: DSEA, Centro Piaggio UNIPI



2 March, 2006

DSEA



Formation Flight



- Traditional Approaches (Manned)
 - Manual Control, Visual Cues
 - Well Defined Line of Command
- Formation Controller (FC)
 - Main Objectives:
 - To maintain Formation Geometry: inter-aircraft distances must be kept constant
 - To make each aircraft follow a prescribed path
 - Gain Computation
 - based on Linear Quadratic Optimal Control Methods, if Perturbations from Trim Trajectory allow



2 March, 2006

DSEA



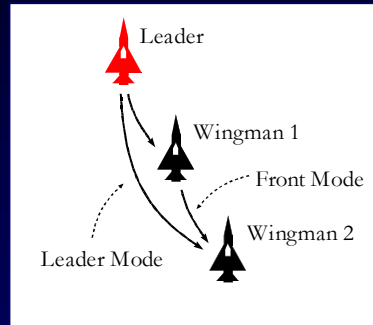
Formation Flight



Two different Strategies

Leader Mode: Both Wingman1 and Wingman2 take the trajectory reference from the Leader of the formation (WVU F22 Experiment)

Front Mode: Each aircraft takes its reference from the preceding one. Here, Wingman1 refers to the Leader and Wingman2 refers to Wingman1



2 March, 2006



Formation Flight



• FC => Formation Geometry

Each Vehicle:

- acquires its position $P = (X, Y, H)$ from a GPS-based system, for instance
- receives, through radio communication channels, other aircraft position information $P_R = (X_R, Y_R, H_R)$
- The position error inside the formation is therefore $\Delta P = P_R - P$, and constitutes the input to the FC controller

• FC => Path Following

- The FC receives path information in terms of velocity, heading and altitude $TR = (VR, HR, \psi R)$, from the reference (Leader, Wingman, Virtual Leader, Ground Station,...).
- The received Data is therefore $RR = (XR, YR, HR, VR, \psi R)$,
- The commanded trajectory for inner loop controller is $TC = TR + \Delta T$, where ΔT is the correction output of the formation controller.



2 March, 2006



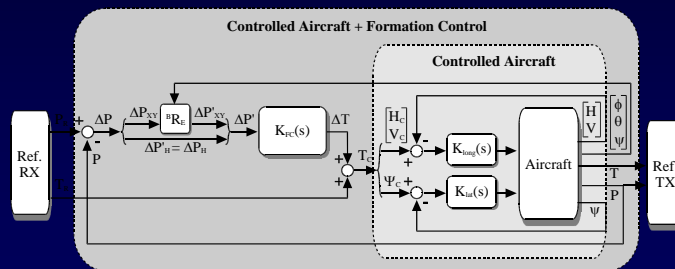
Formation Flight

- Position error $\Delta P = P_R - P$ decomposed into $[\Delta P_{XY}, \Delta P_H]$ and converted to body frame
- Then yielding the input to the controller: $[\Delta P'_{XY}, \Delta P'_H]$
- And the FC controller correction

$$\Delta T = K_{FC}(s)\Delta$$

- Convex combination of multiple position error sets can be used to make formation less rigid

$$\Delta P_W = \sum_{i=1}^m k_i \Delta P_i, \quad \sum_{i=1}^m k_i = 1 \quad k_i > 0 \quad \forall i$$



2 March, 2006

DSEA

Formation Flight Considerations

- Different Levels of Cooperation influenced by many Factors:**

- Capability of Information Exchange
 - Open Channels
 - Stealth
- Necessity of Point-to-Point relative Position
 - Looseness of Formation
- Level of "Intelligence"
 - Trade-off between Complexity and Cost
- Mission Requirements and Specifications

- Modeling**

- Inner Stability has higher Bandwidth
 - Model of entire Formation as a single dynamic System
 - Control with respect to a not-necessarily-physical-point \Rightarrow Formation Geometry Center
- Derive control Objectives from natural migratory Birds Behavior
- Challenge: Mix possibly contrasting control Objectives maintaining Formation Robustness



2 March, 2006

DSEA



Formation Reconfiguration



Standard Equations of Motion in compact Form

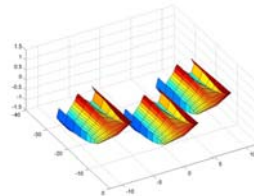
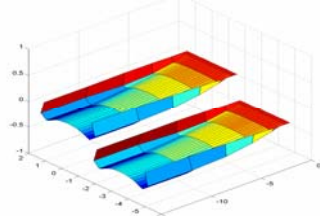
$$\dot{V} = \frac{T-D}{m} - g \sin \gamma - \frac{\Delta D_i}{m}$$

$$\dot{\gamma} = \frac{g}{V} \left[\left(n + \frac{\Delta L}{mg} \right) \cos \phi - \cos \gamma \right]$$

$$\dot{\chi} = \frac{g \left(n + \frac{\Delta L}{mg} \right) \sin \phi}{V \cos \gamma} + \frac{\Delta Y}{mV}$$

$$\dot{X}_f = \dot{X}_i + \frac{1}{2} \rho V^2 S (\Delta_f \cdot C_{Ff})$$

$$\Delta_f = \begin{pmatrix} 1/m & 0 & 0 \\ 0 & \cos \phi / mV & 0 \\ 0 & \sin \phi / (mV \cos \gamma) & 1/mV \end{pmatrix}$$



2 March, 2006



Formation Reconfiguration



Geometry is attained maintaining a prescribed Distance from a Reference Point

Kinematics relating Reference and i-th Aircraft

$$\dot{P}_r^O = \dot{P}_i^O + V_{i,r}^O + \Omega_i^O \times R_{i,r}^O$$

$$V_r^i = V_i^i + V_{i,r}^i + \Omega_i^i \times R_{i,r}^i$$

$$\gamma_e = \gamma_r - \gamma_i \text{ and } \chi_e = \chi_r - \chi_i.$$

Formation Geometry Center

- Improvement on L-W Structure, not capable of handling complex multi-vehicle Tasks
- Aircraft do not refer to each other, rather they maintain a "Distribution"
- FGC : imaginary Point = Geometrical Center of Aircraft Distribution
- Each Aircraft must keep a prescribed Distance from the FGC



2 March, 2006





Formation Reconfiguration



- Control Objectives inspired by natural Behavior of migratory Species
- Each Aircraft has the Capability of sensing other Aircraft Movements from their nominal Position
- Control System provides both Trajectory Tracking and Formation Geometry Keeping



Geese and Swans

- 'Family Groups' : Off-Springs remain with Parents one-two Seasons after Birth
- The Elements in the Group know eachother
- They stay together independently of aerodynamic Benefits

During a migration birds move in a formation:

- Aerodynamic Benefits: Lift Increase and induced Drag Reduction
- 'social Behavior' : some Species tends to move in a Group



Storks

- Non-Family groups: more selfish Species
- They move together to increase Migration Efficiency (food searching and mating season)



2 March, 2006



Formation Reconfiguration



Temporary Position Loss:

- 'Social' Birds: wait for the lost Element: the Trajectory is neglected in order to maintain formation geometry
- 'Selfish' Birds: they wait only if they have Convenience, usually they go on with trajectory tracking
- Inner loop Control using Dynamic Inversion
 - Rotational Dynamics as first Order Lag
- Requirements for outer Loop
 - Desired State in Terms of commanded Variables with Design Bandwidth



2 March, 2006





Formation Reconfiguration

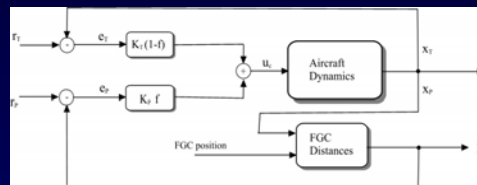


Formation Controller using linearized LQ Methods

- Reproduce the Behavior of migrational Birds
- Two Controllers:
 - K_T provides trajectory tracking $r_T = (V_d \gamma_d \chi_d)$
 - K_P provides formation keeping : each aircraft maintains its relative distance from FGC
- The resulting control law is a convex combination of K_T and K_P

LQ - Servo Design for K_T and K_P

$$u_c = (1 - f) \cdot u_T + f \cdot u_P = \\ = (1 - f) \cdot K_T e_T + f \cdot K_P e_P$$



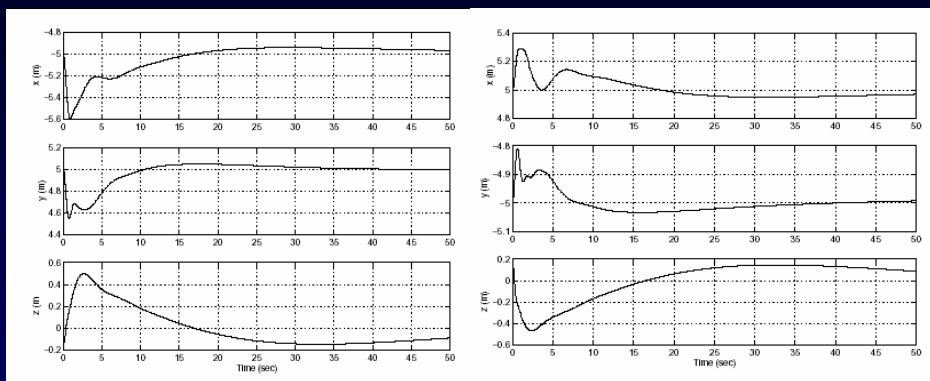
2 March, 2006



Formation Reconfiguration



Two-Aircraft Formation Path Following, -30 deg. Relative distance from FGC



2 March, 2006

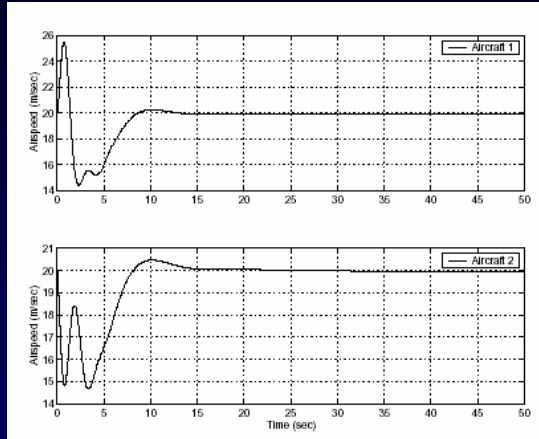




Formation Reconfiguration



A/C 2 slows down and A/C 1 does the same to keep Formation



2 March, 2006



Formation Reconfiguration



Position keeping and Tracking lost

Trajectory keeping and Position lost initially



2 March, 2006





Formation Reconfiguration (Failure)



Objectives

- Investigation of possible Formation Structures
- Capability of maintaining a Formation in the Presence of a Failure
- Emphasis on Optimization with respect to Data Information Transfer
- DATA TX, DATA RX

Working Hypotheses

- Cooperative Formation Management
 - Centralized
 - Decentralized
- Choice of Decentralized Management
 - The Procedure must give the same Result on each Aircraft
- Communication Channels
 - Point-to-Point
 - Broadcast



2 March, 2006



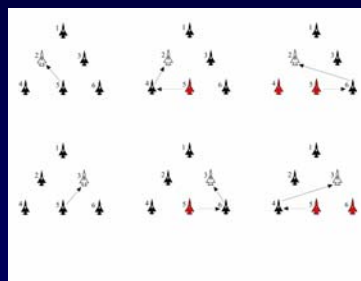
Formation Reconfiguration (Failure)



Graph Theory Approach

- Aircraft Formation as an oriented graph
 - Aircraft positions within a formation \Leftrightarrow nodes
 - Communication channels \Leftrightarrow arcs
- Each arc will have a weight
- Virtual Leader
- Shortest path problem: Dijkstra's algorithm
- Pre set Allowed GEometries

- New Concept: Reconfiguration Maps depending on RX or TX failure
- Describe the maneuvers needed to reach a new Position after a Fault Notification
- RMs are grouped depending on the Number of Aircraft actually occupying the Formation



2 March, 2006





Formation Reconfiguration (Failure)



Each RX device must be able to detect when a communication channel is lost. This means when the corresponding TX has become faulty, the reference aircraft has left the formation, or its own RX is not functioning. While the RX device is deciding whether the channel is definitively lost or the fault is temporary, it holds its output and notifies the formation controller.

The aircraft whose TX fails must be able to detect it because this is needed by the formation reconfiguration procedures. When, for any reason, one aircraft TX stops being operational, that aircraft can no longer be a reference for the others. The TX fault has the effect of "deleting" all outgoing channels. From the point of view of Dijkstra's algorithm, the arcs leaving that node may be assigned a weight equal to infinity. All the aircraft that used the faulty one as reference must reconfigure. From the standpoint of communication reconfiguration, the case of an aircraft loss corresponds exactly to the broken TX case.

After a failure, a fast reconfiguration procedure must be run to restore formation-keeping as quickly as possible. When an aircraft detects that its own RX is faulty, it must reconfigure the formation controller to use the VL information, if no connection to the VL is available, the aircraft cannot remain in the formation. When an aircraft detects a TX fault in its reference, that is it loses its present communication channel, it must use a different node as reference.

To keep all aircraft informed of what is happening to a specific node, and which of the nodes are active (that is nodes occupied by a vehicle), an additional broadcast communication channel is introduced that transmits data at low frequency; this new channel is known as the BC.

During the mission, the reference trajectory could be provided in two ways. It may be stored in one (or more) onboard computers, or it may be provided remotely from a ground station as well as from a manned aircraft. In both cases, not all the aircraft may be required to know the reference trajectory. The reference trajectory can be seen as the effective leader of the formation, by introducing an imaginary point moving in the space, tracking the path prescribed for the formation and rigidly followed by all the aircraft of the formation.



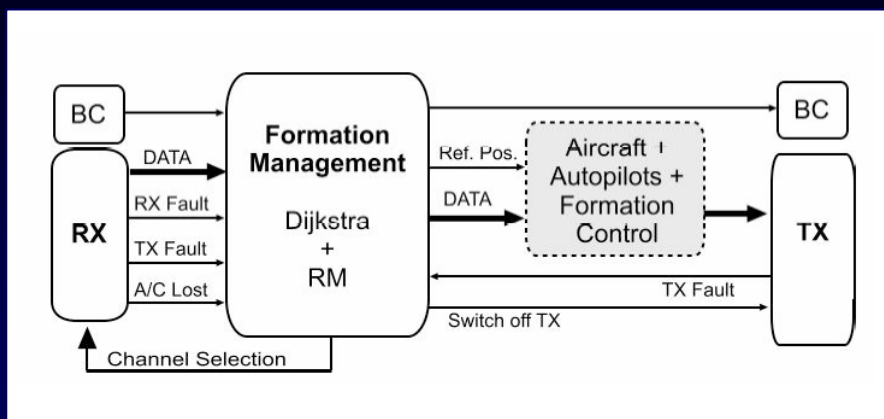
2 March, 2006



Formation Reconfiguration (Failure)



Control System Schematic



- Vehicles Dynamics and Control coded by Simulink Schemes
- Finite State Machine implemented by a Stateflow code



2 March, 2006



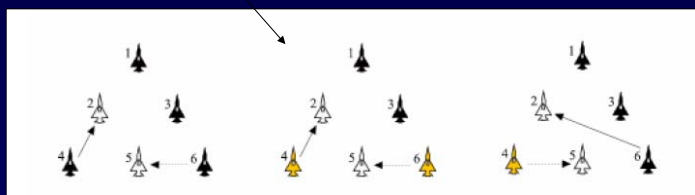
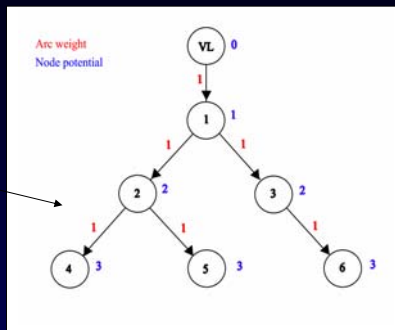


Formation Reconfiguration (Failure)



Shortest Path Tree before Fault

Reconfiguration Maps due to Loss of Aircraft 3



2 March, 2006

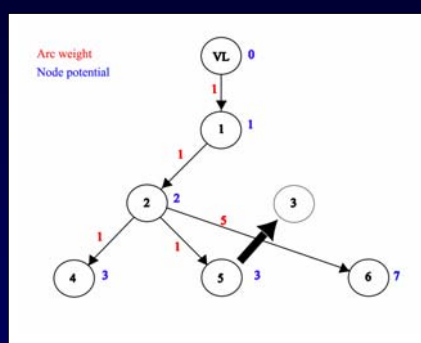
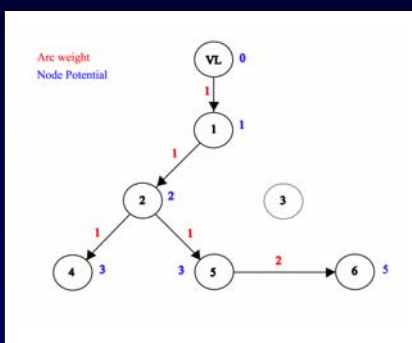


Formation Reconfiguration (Failure)



After aircraft 3 loss each Dijkstra's algorithm gives the Sub optimal solution

Aircraft 5 is chosen to replace the free position

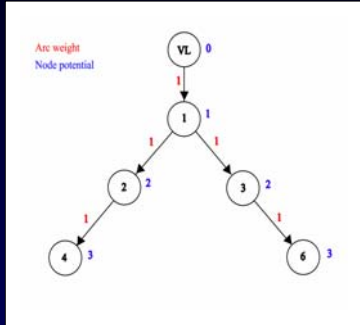


2 March, 2006



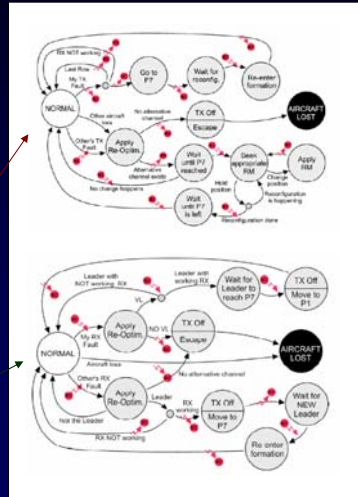
Formation Reconfiguration (Failure)

New configuration after aircraft loss



Management Logic for TX Failure

Management Logic for RX Failure



2 March, 2006



Formation Reconfiguration (Failure)



2 March, 2006





Application



2 March, 2006



Path Planning and Task Assignment



Complexity Considerations

- N Targets
 - Still or moving
 - Positions known at the beginning of the mission
 - Positions may be known with uncertainty
 - Targets are moving => When initial fix is reached they may have moved away
 - Targets could be:
 - Observed only
 - Hit => characteristics of pursuer need to be established

- sub-teams
- cooperation
- random search intractable
- "the" solution online intractable
- approach: hierarchy

- Maximum M Aircraft
 - The number of employed aircraft depends on particular mission
 - Reconnaissance mission:
 - Aircraft have no *capacity* saturation
 - Combat mission:
 - Each aircraft can be pointed to a maximum number of targets
- Areas to be avoided may exist

1. Definition of number of aircraft needed for the mission
2. Initial target assignment
3. Optimal routing with and without obstacles
4. Target re-assignment and re-routing



2 March, 2006





Path Planning and Task Assignment



- Targets Position "almost" exactly known
 - Deterministic Assignment
 - Targets Position unknown or moving Targets
 - Positions are known with uncertainty
 - Targets may move after initial assignment
 - Search may be activated when in proximity of estimated positions
- => Stochastic Assignment



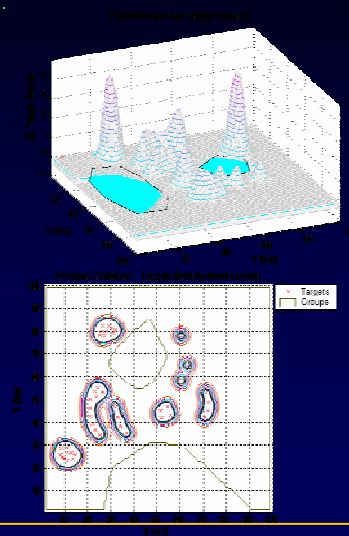
2 March, 2006



Path Planning - Task Assignment



- A position probability function (Gaussian) is associated to each target
 - Mean Value is target initial/estimated position
 - Standard deviation depends on target mobility, target initial position uncertainty and estimated time to target
- An appropriate density function (negative valued) is used over obstacles' boundaries
- The cumulative target density function over the entire operational area is evaluated
- The target density level curves μ_i are used to identify zones where the target density is higher than a certain threshold



2 March, 2006





Path Planning - Task Assignment



- 7 slowly moving targets with initial position known with uncertainty
 - Each aircraft can approach max. 3 targets
 - Each target is characterized by known motion capability and initial position uncertainty
- =>
- 2 groups results (with 2 and 5 targets each)
 - 3 identical aircraft are selected



2 March, 2006



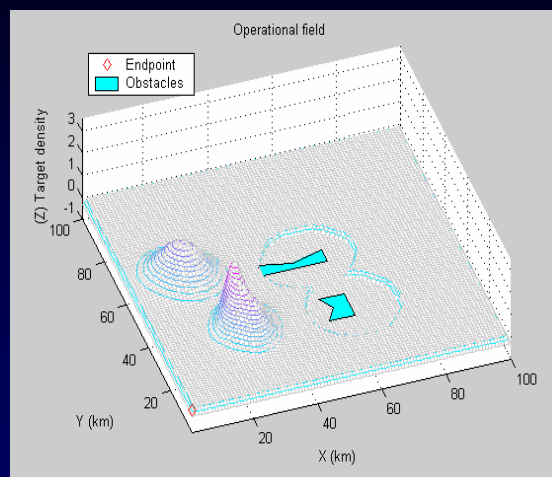
Path Planning - Task Assignment



The target density field is constructed

Dangerous areas are clearly marked by negative field values

Grouping is performed



2 March, 2006





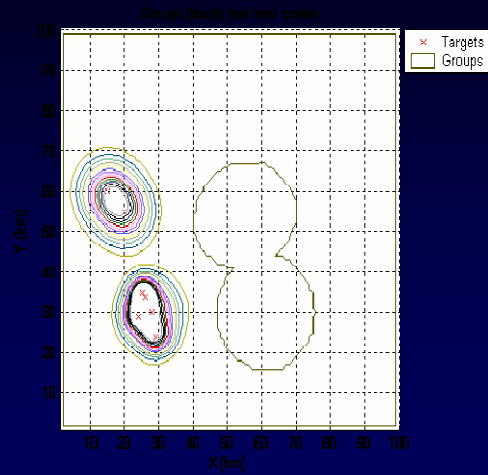
Path Planning - Task Assignment



Level curves of the target density field are evaluated

The "highest-level" density curve that contains all targets is selected

The dangerous zones are clearly defined



2 March, 2006



Path Planning - Task Assignment

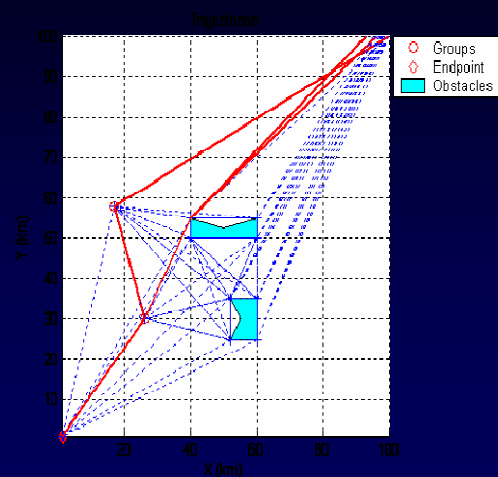


The optimal routes (minimum distance) are computed

Dangerous zones (obstacles) are avoided

One aircraft must reach two groups before saturating its "capacity"

The other two aircraft avoid the obstacle first and reach second group successively.



2 March, 2006



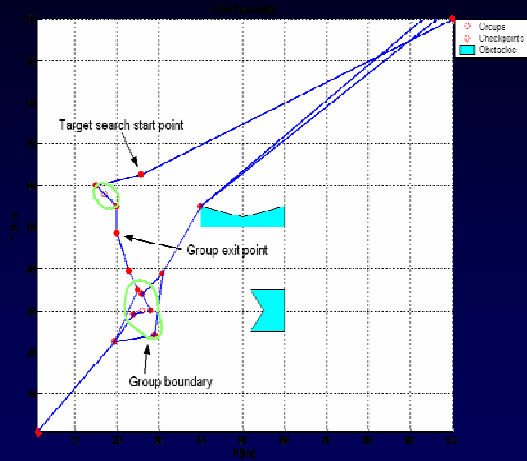


Path Planning - Task Assignment



Target search may start at a given distance from group center or on the group boundary itself

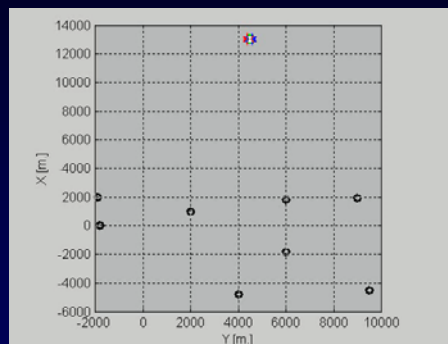
Inside the group the shortest path among designated targets is selected



2 March, 2006



Path Planning - Task Assignment



2 March, 2006





Task Allocation Problem: Task Definition



- Problem Definition
 - Multiple UAV Scenario
 - Multiple moving Targets (Partially known)
 - Known Environment
- Approach/Requirements
 - Coarse Task Definition (Identification, Attack, Verification,..)
 - Time Constraints due to Platform Limitations (Fuel, Visibility,..)
 - Quick Online Re-Allocation



2 March, 2006

DSEA



Task Allocation Problem: Task Definition



- Literature
 - Degree of Complexity
Increase searching for
Global Optimal Solution
 - MILP Approaches (Chandler,
How, Schumacher,..)
 - Improvements with Loitering
Time Concept, Path
Elongation Technique, ..
- Approach
 - Pipeline Approach with
computationally intensive
Tasks performed off-line

N Vehicles $\{A_1, A_2, \dots, A_N\}$

M Targets $\{T_1, T_2, \dots, T_M\}$

3 Tasks:
[Identification, Attack, Verification]

Sequential Tasks

Time after which
Next task begins

$\Delta_{\text{target}}^{\text{task}}$



2 March, 2006

DSEA



Task Allocation Problem: Algorithm Structure



- Optimality
 - Ensured with stationary Targets
 - Unfeasible with moving Targets (suboptimality in some sense)
 - 2-Steps Algorithm
- Offline phase
 - Construction of a proper Map of the Environment based on a priori Knowledge of Scenario
 - Extraction of Costs information from the Map
- Mission-Time phase
 - Managed Costs to customize Hungarian Algorithm
 - All three Tasks for each Target can be considered
 - Only sequential at this point



2 March, 2006

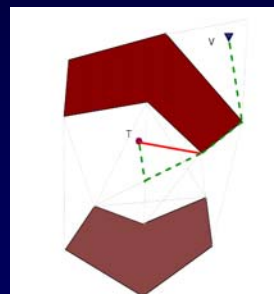
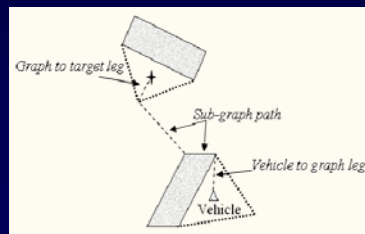
DSEA



Tesselation Graph



- Phase 1 (Off-line):
 - *Tesselation-Graph* (TG) based on triangulation algorithm.
 - TG divides the XY Plane in Triangle-shaped areas.
 - During the Mission. Vehicle flies from the Area containing the Vehicle itself to the Area containing the assigned Target using inter-area path.
 - The dimension of each Triangle could be an expected Uncertainty measure on Target Position



2 March, 2006

DSEA

Allocation Algorithm

- Phase 2 (Mission-Time): The Allocation Problem is solved by means of a proper Choice of the Costs for the three Tasks on each Target.
 - Costs from the off-line Phase are used and modified with the Score of the Target to determine the Cost of the current Task

$$c_{ik} = \frac{l_{ik}}{V_{A_i}} \cdot P_k$$

- The modified Cost is the Cost for the current Task on Target

$$\begin{cases} \min \sum_{i=1}^N \sum_{k=1}^N c_{ik} x_{ik} \\ \sum_{i=1}^N x_{ik} = 1 & k = 1 \dots N \\ \sum_{k=1}^N x_{ik} = 1 & i = 1 \dots N \\ c_{ik} \geq 0 \\ x_{ik} \in \{0,1\} \end{cases}$$

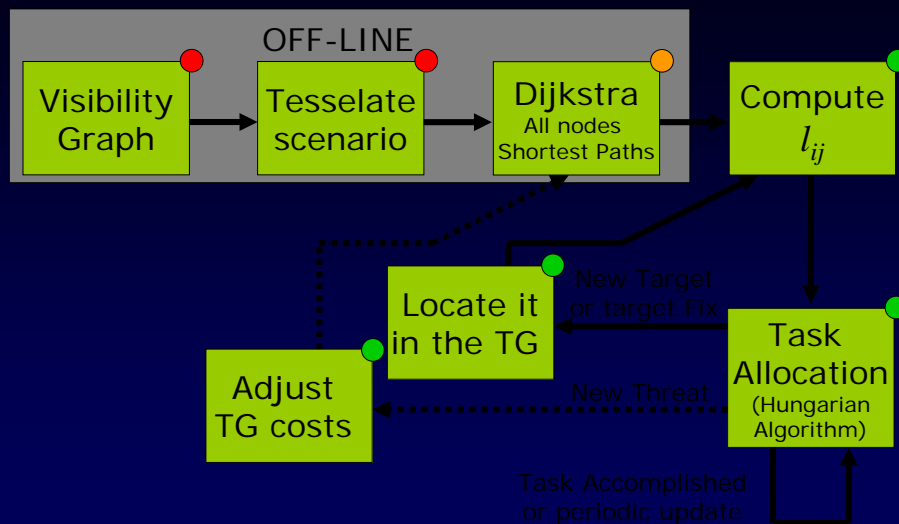
$$\begin{cases} c_{ik}^V = \max_j \{c_{jk}^A\} + \delta_k \cdot \frac{c_{ik}^A}{\max_j \{c_{jk}^A\}} \\ \delta_k \in \mathbb{R}, \delta_k > 0 \end{cases}$$



2 March, 2006

DSEA

Algorithm Flow



2 March, 2006

DSEA



Allocation Algorithm

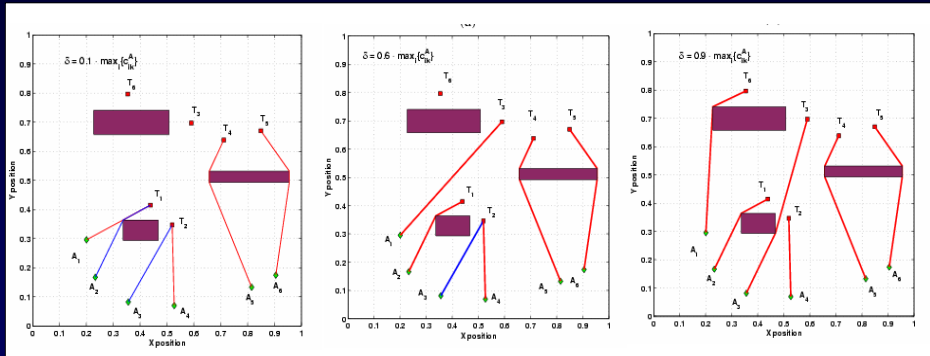


$$\begin{cases} c_{ik}^V = \max_j \{c_{jk}^A\} + \delta_k \cdot \frac{c_{ik}^A}{\max_j \{c_{jk}^A\}} \\ \delta_k \in \mathbb{R}, \delta_k > 0 \end{cases}$$

Influence of δ on Cooperation
2 Tasks

High Cooperation

Low Cooperation



2 March, 2006

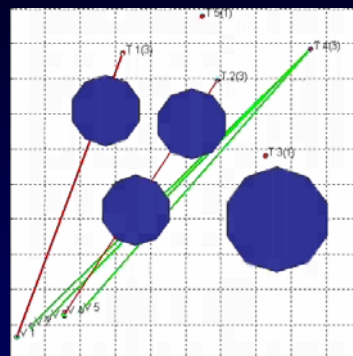
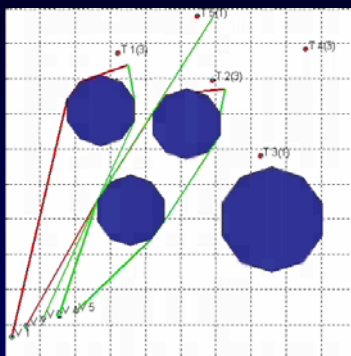


Allocation Algorithm - Example



Low δ , moving targets, T3 and T4 low priority (cooperative)

High δ , moving targets, T3 and T4 low priority (non cooperative)



2 March, 2006





Vision-based Formation Flight



- Coordinated / Cooperative control requires more sensors than manned operations
- Autonomous Formation Flight needs precise relative position and attitude feedback
 - Pilots rely on vision only
- Autonomous Refuelling needs very precise positioning accuracy
 - Very difficult tasks for pilots as well
- Artificial Vision may be useful



2 March, 2006



Vision-based Formation Flight



- 2 Aircraft Scenario:
 - Leader (flies its own trajectory)
 - Wingman (flies at appropriate lateral and forward clearance)
 - Close Formation Situation
- Wingman Control Systems require:
 - Leader relative Displacement
 - Leader Trajectory Information
- A Video Camera is placed on the Wingman
 - Optical markers located on the Leader (possibly high power IR Light Emitting Diodes)
 - The vision system identifies such markers and estimates relative distances and attitude



2 March, 2006

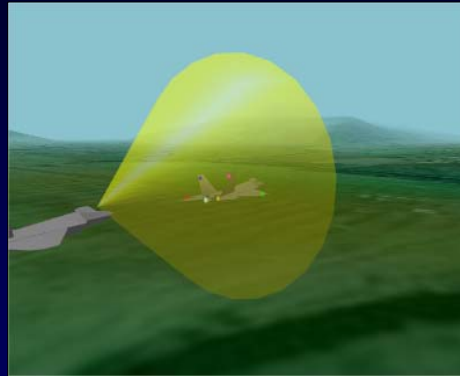




Vision-based Formation Flight



- With a Vision Feedback System Distances and relative Attitudes can be estimated directly
 - Distances are measured in Wingman body/camera axis
 - No double GPS error
 - Estimation of velocity requires time differentiation of the position signals (noisy)



2 March, 2006

DSEA



Autonomous Aerial Refueling



- Probe and Drogue
 - A flexible hose with a basket (drogue) at the end
 - The drogue floats in the air and is quite sensible to atmospheric disturbances
 - The UAV must put its probe into the drogue autonomously
- The control system must know relative displacement between the UAV and the drogue
 - Required precision : few centimeters
 - The tanker knows its position (via GPS) but not that of the drogue



2 March, 2006

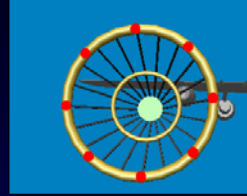
DSEA



Autonomous Aerial Refueling



- A Video Camera is placed on the UAV
 - Some optical markers are placed on the drogue (possibly high power IR Light Emitting Diodes)
- The vision system identifies such markers and estimates relative distances and orientation



2 March, 2006

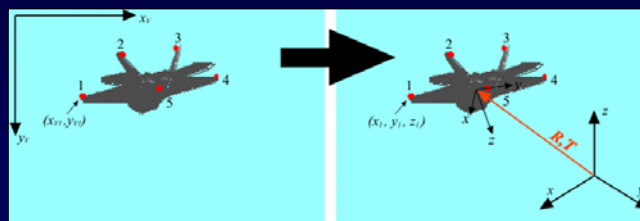
DSEA



Pose Estimation



- Key technique: **Pose Estimation**
 - "Find the rotation matrix R and translation vector T that best map (in the mean square sense) a set of video image 2D points to a known 3D points set"
 - Commonly used in Robotics
 - Different Algorithms: deterministic execution or iterative



2 March, 2006

DSEA



The Basic Vision Algorithm



- LHM
 - Iterative
 - Minimizes Collinearity Error
 - Proven to be globally convergent
 - Fast and accurate
 - Needs exactly known correspondence between each recognized 2D point and the 3D markers
 - =>
 - The optical markers must be easily distinguishable one from the other
 - If markers are Light Emitting Diodes (LEDs) they must have some kind of frequency modulated light
 - =>

Complex and expensive in general



2 March, 2006



Enhanced LHM



- Use collinearity Error to verify correctness of 2D-3D correspondence
 - Test all possible correspondence sets and choose the best one (experimental result show a high error ratio) => $N!$ possible combinations => Unfeasible in Real Time

Solution:

- Place in a particularly ordered pattern the 3D points so that their 2D images are quite far from the one from the other, in typical relative displacements
- Enclose the 2D vertex images into a polygon, order the polygon vertices and test all possible sequences
- N possible sequences => reasonable increase in computations



2 March, 2006





Sources of Errors in Real Environment



LEDs/Markers may not be easy to identify:

- Camera resolution
 - The lower the resolution the higher the quantization error
 - At high distances a LED's image occupies few pixels and may be attenuated or not appear at all
- Environment
 - The Sun is a high power source of IR radiation
 - The clouds (H_2O) reflect it (the Sky appears dark)
 - Trees and grass highly reflect it (chlorophyll)
 - The same aircraft body reflect IR radiation
- Visibility
 - Some LEDs may be hidden (behind parts of the aircraft, the probe etc.)
 - Some LEDs may be outside the viewing cone
 - LEDs emission angle



2 March, 2006

DSEA



Robust LHM



Must identify which LEDs are not identified among the required 3D configuration

- Combination of three techniques:
 - Smart marker ordering; two techniques:
 - Convex hull
 - Triangle fan
 - 2D markers spatial coherence: match markers that are near in the camera plane between successive frames
 - Estimation of body-camera relative dynamics: compute the velocities and the accelerations of the estimated frame and apply threshold to validate the estimate



2 March, 2006

DSEA



Simulated Formation Flight



- A model aircraft
 - World War II P-51 Mustang
 - 5 LEDs: on the wingtips, the rudder and the two elevators
 - LEDs are non coplanar => limited Euler angles excursions
 - Moved by an actor in front of a fixed camera
- Hardware setup
 - Low power IR LEDs (900 nm wavelength) small aperture angle (± 15 deg)
 - Common webcam (resolution 640 x 480)
 - Visible light filter (low pass filter)
 - Band pass filter exist but allow very small incidence angles
- Environment
 - Sunny day
 - Sun from the back (camera on a tripod)
 - Scene: 70 % sky, 30 % Pisa skyline and hills on the back

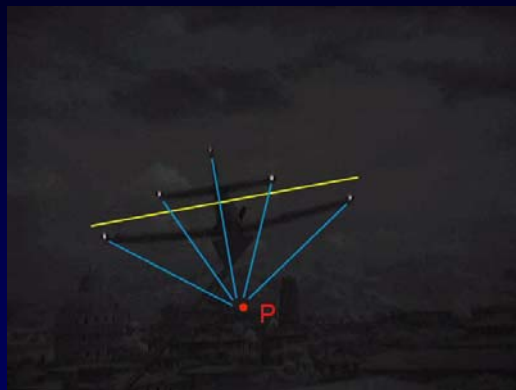


2 March, 2006

DSEA



Sample Triangle Fan



2 March, 2006

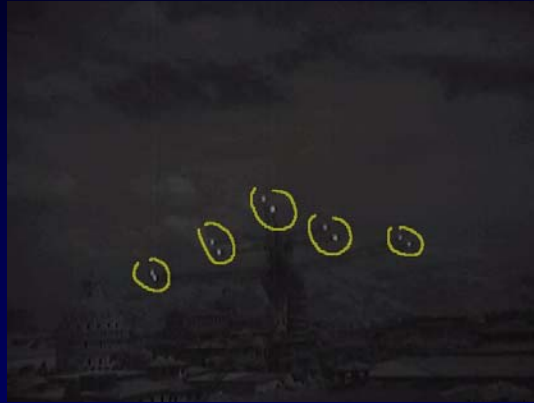
DSEA



Sample 2D Coherence Map



Distance between frames: 5 frames (Camera FPS: 25)



2 March, 2006

DSEA



Sample Pose Estimation



- 5 LEDs are identified (red squares)
- The order is identified (red polygon)
- LHM computes the relative position \mathcal{T} and attitude \mathcal{R}
- The 5 markers are projected back onto camera plane for verification purposes (blue squares)
- If blue and red squares match, pose estimation is good



2 March, 2006

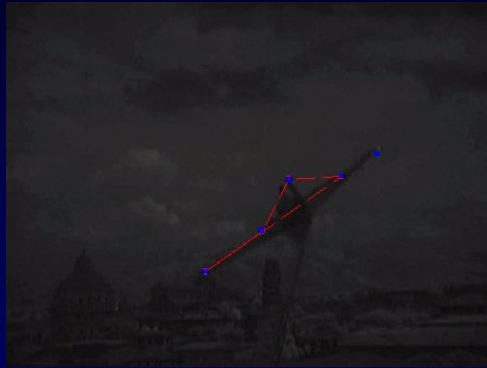
DSEA



Sample Pose Estimation (2)



- 4 LEDs are identified
- The triangles fan Technique and 2D coherence identify the order
- LHM computes the relative position and attitude using 4 markers ONLY
- The 5 markers are projected back onto camera plane
- The upper blue square matches the position of the missing LED.
- pose estimation is good



2 March, 2006

DSEA



Current Hardware Modification



Automatically generated Leader Motion



2 March, 2006

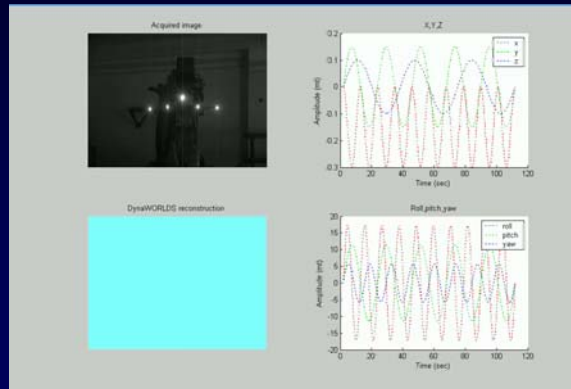
DSEA



Analysis Tool



- An Analysis Tool was developed
 - Plot position and Euler Angles
 - Compare camera image with a CG reconstructed Image



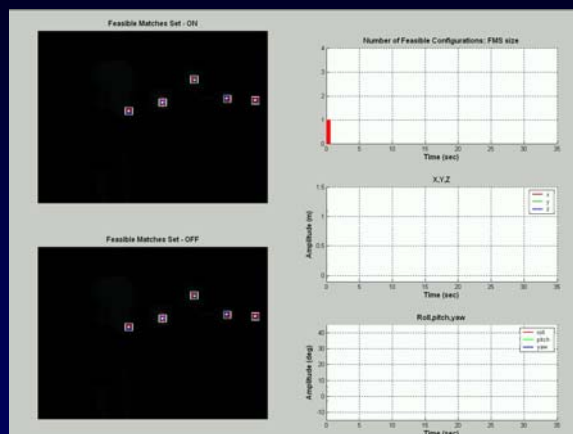
2 March, 2006



Analysis Tool



- Use of Feature Matching



2 March, 2006





Conclusions



- The Technique appears reliable
 - If the LEDs are correctly recognized, pose estimation is good
 - If some LEDs are lost, a range of possibilities exist to maintain robust performance
- Computation time is low
 - Practically shown, although iteration number is not theoretically bounded
- Future work:
 - Engineering: LEDs and camera systems
 - Model based filtering for fault detection of estimations
 - Two cameras with different focal lengths: one fixed with wide lens, one with a zoom controlled automatically in pan and tilt tracking the aircraft
 - More testing



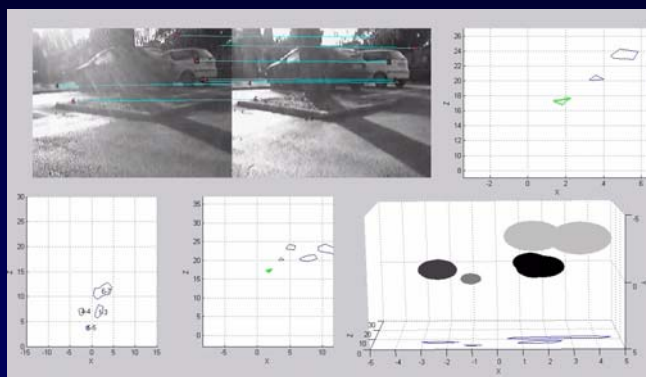
2 March, 2006



Conclusions



- Example for UGV
 - Golf kart for physically disabled players
 - Limited mobility
 - Blindness



2 March, 2006

