In the Name of GOD

Guidance and Navigation I

UAV Guidance

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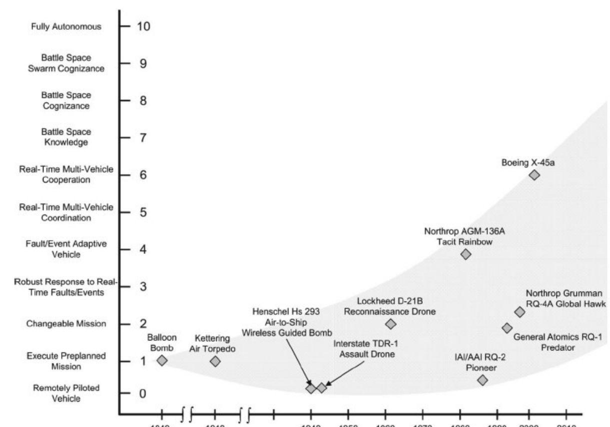
UAV Guidance

- Classification of UAVs from Guidance System Point of View
- Autonomy Levels for Unmanned Systems
- UAV Guidance Problems
- Application of Tactical Guidance Laws in UAVs
- Terrain Following/Terrain Avoidance
- Cooperative Guidance
- Optimization of Guidance Algorithms

Classification of UAVs

- **Guidance System**
  - Remotely controlled
    - from a location that may even be thousands of kilometers away
  - Autonomous
    - **Definition 1**: a pre-programmed flight from take-off to landing without further instructions from outside
    - **Others**: An autonomous system must include an element of artificial intelligence to be able to make its own decisions without human interaction or pre-programming.

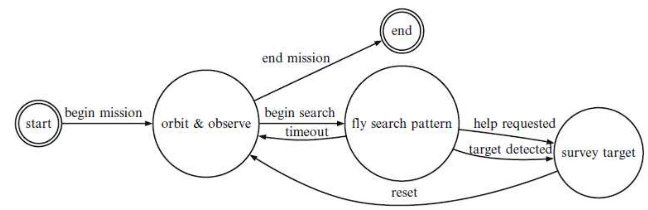
Degree of Autonomy



Degree of Autonomy

- **Coordination**
  - The strongest degree of cohesive team action
  - All agents share a common team objective(s)
  - There is no conflict of interest among the agents
  - An agent is a resource that may be over-utilized or under-utilized
- **Cooperation**
  - in addition to the team objective function, Each agent has a private objective function which he attempts to optimize
  - The private and team objective functions are weighted (w)
  - w=1 means self interest, w=0 means strict coordination
- **Collaboration**
  - a loose form of team interaction (e.g. task assignment or resource allocation)

Behavior-based autonomy



- behaviors are sequenced using a finite state machine that defines the states or behaviors that are possible and the events or triggers that cause the robot to change from one behavior to another.

UAV Guidance Problems

- Trajectory/Waypoints Tracking
- Target Tracking
- Terrain Following/Terrain Avoidance
- Collision (Obstacle) Avoidance
- Intercept
- Cooperative missions
  - Cooperative Search and Localization
  - Cooperative Track
  - Cooperative Attack
  - Cooperative Defense
  - Formation Flight

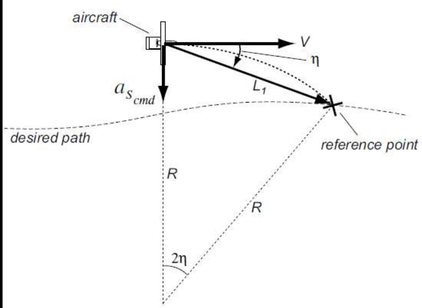
Application of Tactical Guidance Laws in UAVs

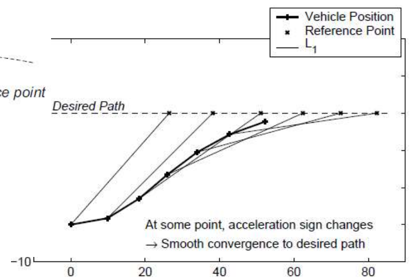
- Proportional navigation-based optimal collision avoidance for UAVs, 2004.
- Flying in formation using a pursuit guidance algorithm, 2005.
- Robust trajectory-tracking method for UAV guidance using proportional navigation, 2007.
- Vision-Based Road-Following Using Proportional Navigation, 2010.
- An improved line of sight guidance law for UAVs, 2013
- An Improved Proportional Navigation Guidance Law for Waypoint Navigation of Airships, 2017
- An improved integral light-of-sight guidance law for path following of unmanned surface vehicles, 2020

Trajectory Tracking

- A New Nonlinear Guidance Logic for Trajectory Tracking, 2004
- Simulation Code

$$a_{s_{cmd}} = 2\frac{V^2}{L_1}\sin\eta$$





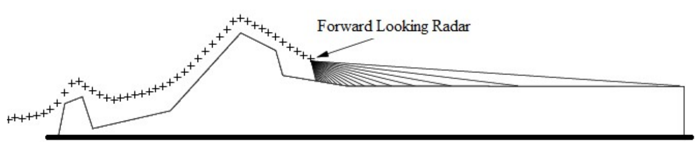
Terrain Following

- Objectives:
  - To remain as closely as possible above a given distance (clearance height) from the ground during the flight
  - To fly fast enough

  => to minimize the danger of being detected or intercepted.
- Typically, development of a TF guidance system consists of three steps:
  - trajectory generation (planning) to maximize both survivability and mission effectiveness,
  - Guidance law to track the trajectory within the maneuvering capabilities,
  - sensor blending for terrain data update,

Terrain Following Radar

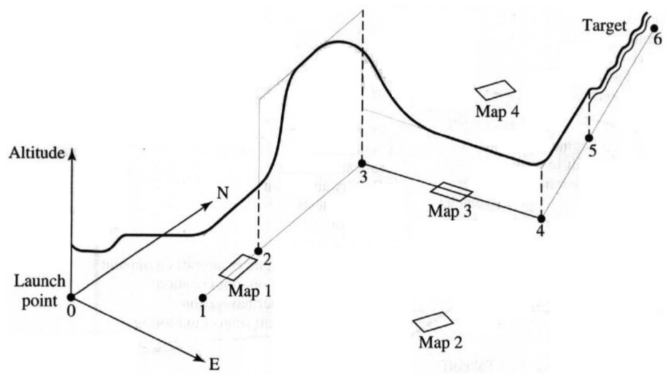
- A forward looking Terrain Following Radar (TFR) may be used to provide range and angle information of the future points on the ground.
- problems with using a TFR
  - Cost
  - Complexity
  - The vehicle is detectable



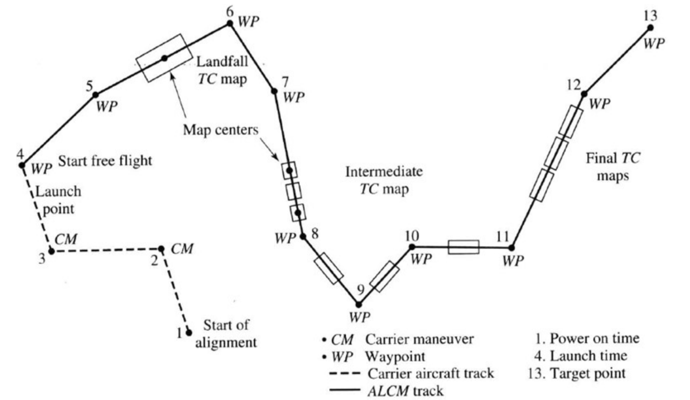
Terrain Aided Navigation (TAN)

- INS + A Radar altimeter + A stored digital terrain map + A barometric altimeter
- A Kalman filter tries to estimate the current position.
- The Kalman filter is driven by the error between the absolute height read from the barometer with the expected absolute height (the sum of the radar altimeter reading and the map height at the estimated position).
- Requirements:
  - An accurate navigation system
  - An accurate stored digital terrain

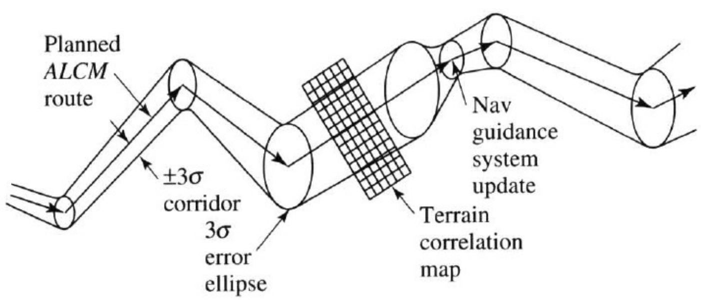
TERCOM



Sample Mission Diagram of an Air-launched TERCOM

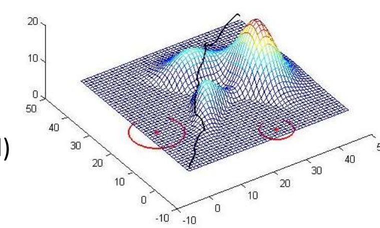


Error Ellipses



Terrain Following/Terrain Avoidance

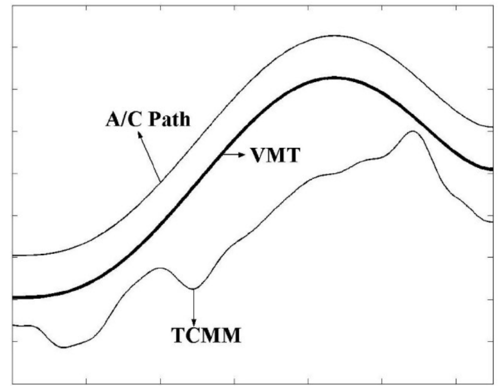
- TA is more difficult than TF.
- TF/TA Constraints
  - Initial and target position
  - Kinematic constraints
  - Ride comfort (for manned)
  - Navigation accuracy
- TF/TA Performance Metrics
  - Total risk from the enemy and ground collision
  - Time at which target is reached
  - Terrain following performance
  - Fuel consumption



Simplified TF-TA Problem

- TF/TA problem is simplified if the problem is split into two parts:
  - A nominal route is found to the target:
    - This is a path, possibly hundreds of kilometers long, through a series of way points
    - It is assumed to take account of the **coarse features** of the terrain and the **known defenses**.
  - An improved route in a corridor several kilometers wide about the nominal route is constructed by some optimization technique.

Terrain Continuous Mathematical Model (TCMM) Virtual Modified Terrain (VMT)



Optimal TF/TA Path Planning [1988]

- Cost function

$$J = \int_0^{t_f} (W_1 C_t^2 + W_2 h^2 + W_3 f_{TA})\,dt$$

- C_t: Cross track deviations: to prevent the aircraft from wandering too far away from the specified waypoints.
- h: altitude from sea level
- f_{TA}: penalizes the generated routes that come dangerously close to "known" ground threats.
- Δh_{AS}: height above SAM site
- R_S: Slant Range to SAM site

$$f_{TA} = \sum_{i=1}^{N_{site}} \left\{ K_i \frac{\Delta h_{ASi}}{R_{Si}} \right\}^2$$

Optimal TF/TA Path Planning

- State equations of lateral aircraft dynamics:

$$\begin{aligned}
\dot{x} &= V_G \cos \Psi & ;\ x(0) &= X_0 \\
\dot{y} &= V_G \sin \Psi & ;\ y(0) &= Y_0 \\
\dot{\Psi} &= \dot{\Psi} & ;\ \Psi(0) &= \Psi_0 \\
\ddot{\Psi} &= w_0 (u - \dot{\Psi}) & ;\ \dot{\Psi}(0) &= \dot{\Psi}_0
\end{aligned}$$

- w_o: the inverse time constant of the turn rate control system
- u: turn rate command (input signal)
- V_G: ground speed

$$\frac{\dot{\Psi}(s)}{U(s)} = \frac{w_0}{s + w_0}$$

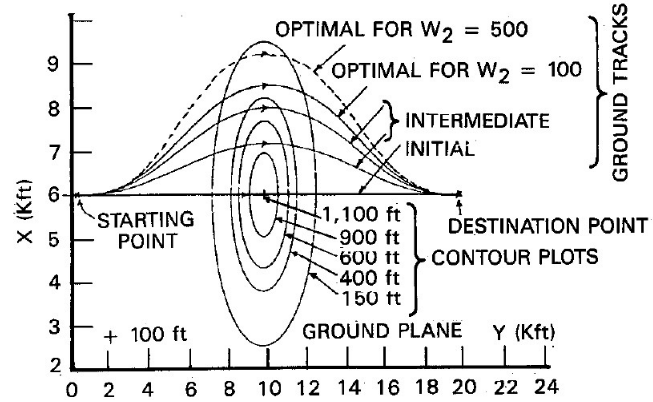
Optimal TF/TA Path Planning

- Terminal Constraints: depends to the application, e.g.

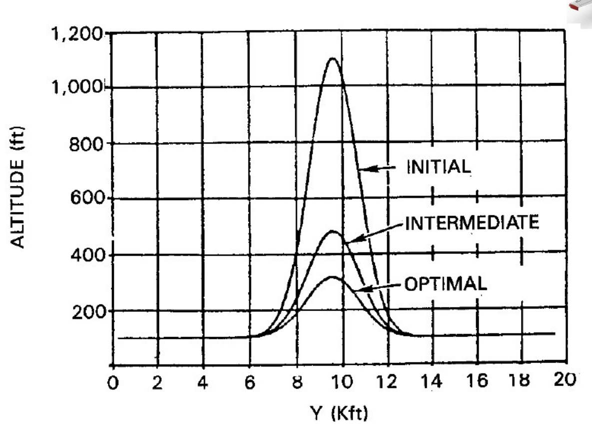
$$x(t_f) = x_f$$
$$y(t_f) = y_f$$
$$\Psi(t_f) = \Psi_f$$
$$\dot{\Psi}(t_f) = \dot{\Psi}_f$$

[Ref] Terrain Following / Terrain Avoidance Path Optimization using the Method of Steepest Descent, 1988.

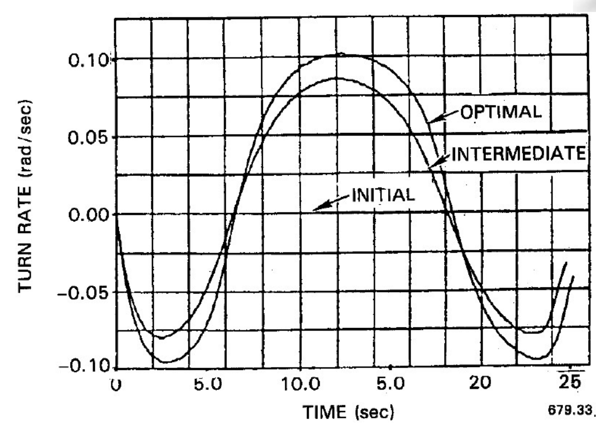
Optimal TF/TA Path Planning



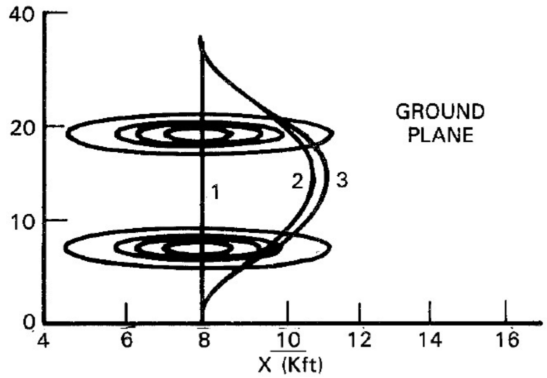
Optimal TF/TA Path Planning



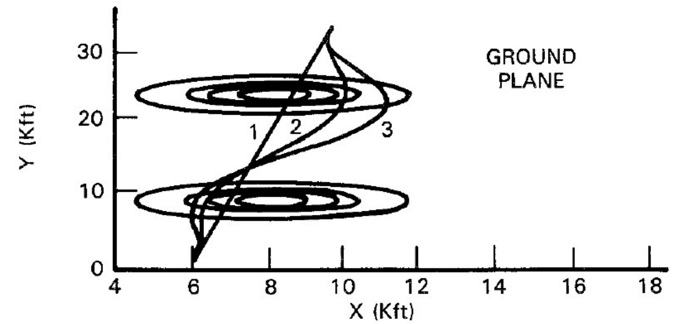
Optimal TF/TA Path Planning



Optimal TF/TA Path Planning

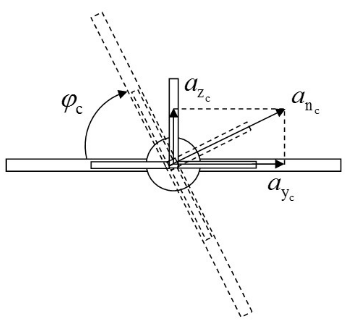


Optimal TF/TA Path Planning



STT to BTT Conversion

- a_{yc} and a_{zc} must be converted to ϕ_c and a_{nc}!



$$\varphi_c = \tan^{-1}\left(\frac{a_{y_c}}{a_{z_c}}\right)$$

$$a_{n_c} = -\operatorname{sgn}(a_{z_c})\sqrt{a_{y_c}^2 + a_{z_c}^2}$$

$$\dot{\theta}_c = \frac{a_{n_c}}{v}$$

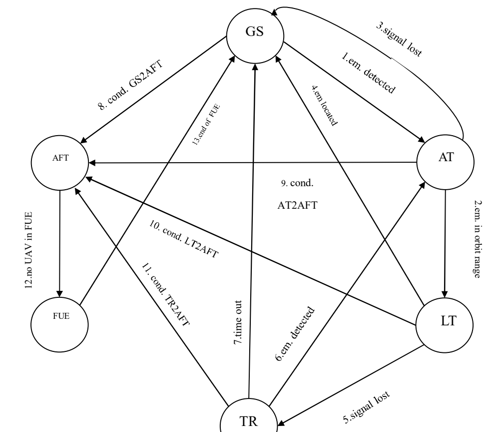
Cooperative Search and Localization

- **Localizing RF Targets with Cooperative Unmanned Aerial Vehicles, 2007,** Daniel J. Pack, et. al.

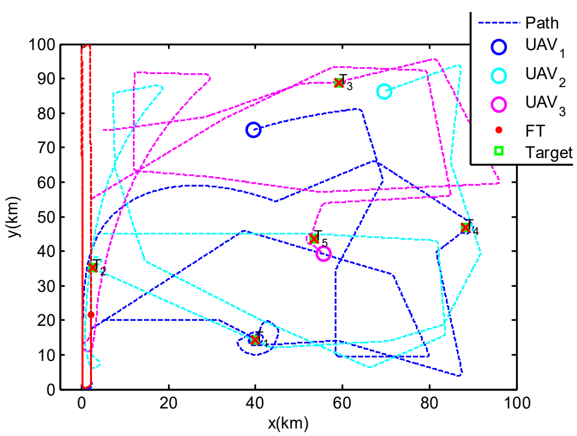
Cooperative Search and Localization

- Sensors:
  - RF sensors
  - GPS
- Objective
  - Minimization of overall time to search for a group of targets
  - Minimization of the final localization error
- Working modes of UAVs
  - Global Search (GS)
  - Approach Target (AT)
  - Locate Target (LT)
  - Target Reacquisition (TR)

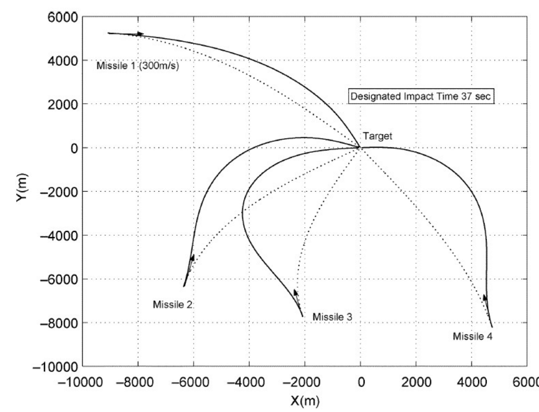
State Transition Diagram



Cooperative Search and Localize

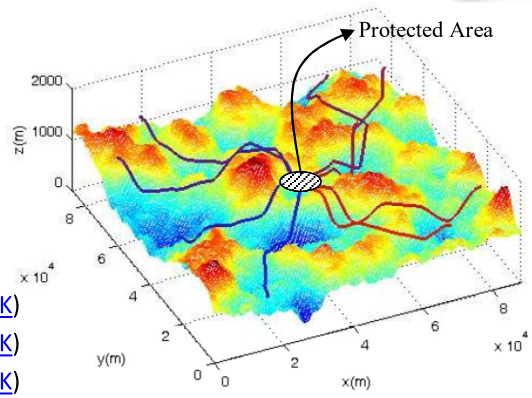


Cooperative Attack



- [Sample Simulation for Two agents]

Cooperative Defense



- Video 1 (LINK)
- Video 2 (LINK)
- Video 3 (LINK)

Optimization of Guidance Parameters

- Simulation Model
- Cost Function
- Optimization Results