PROPORTIONAL NAVIGATION WITH ADAPTIVE TERMINAL GUIDANCE FOR AIRCRAFT RENDEZVOUS (PREPRINT)

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- PN with adaptive terminal guidance is shown to be a viable guidance method for aircraft rendezvous in 6DOF simulation.
- Adaptive PN and Velocity controller combination is shown to effect successful rendezvous.
- Adaptation accounts for errors caused by assumptions (stationary RZ location), wind, and tanker maneuvers.

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Proportional Navigation with Adaptive Terminal Guidance for Aircraft Rendezvous

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Background

• Automated Aerial Refueling (AAR) requires receiver-to-tanker rendezvous
• A trajectory/guidance algorithm is necessary to provide a path/FCS commands for the aircraft rendezvous
  – Optimization algorithms are computationally intensive
  – Geometric solutions limit UAV maneuvering
  – Trajectory solutions may “jump” around

Current CONOPS for AAR is the trajectory algorithm brings the UAV to a 1-NM trail position, where a tanker relative control law is engaged

Very difficult to embed an iterative optimization algorithm in a FCS running at high rates

Geometric solutions (even when iterative) may not control speed or provide a smooth rendezvous (zero turn rate at RZ)

Useful to look at a simple algorithm that meets rendezvous contraints (same V, Psi, Pos at same time) that can be embedded in a FCS
## Requirements

- Able to embed into UAV FCS and run real-time
- Use same information as FCS (AAR PGPS)
- Must obey vehicle limits, and tactical and operational CONOPS
- Execute successful rendezvous

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Must be able to embed guidance algorithm into FCS running at high rate

Must use same information as inner/outer loop, Precision Differential GPS
Proposed Guidance System

- A proportional navigation guidance system with adaptive terminal guidance,

And a velocity control loop that…

- Commands UAV to RZ location with the same speed and heading as tanker, at same time
- Obeys velocity, acceleration, and turn rate limits
- Is robust to winds and tanker maneuvering
Design Approach

Design

- Treat target as stationary, using an adaptive “tanker estimator”, based on kinematics, to determine a rendezvous (RZ) location
- RZ location approaches tanker as receiver’s heading and position approach tanker’s heading and position
- Velocity loop will control speed
- 2-D (constant altitude)

Use “estimator” to determine a target location, prevent prolonged “tail chases”

Wind component

The adaptive terminal guidance pronav will provide a turn rate command to align UAV heading with tanker heading at or before rendezvous location

Two main coordinate systems, flat earth N-E and RFE (tanker relative)

Tanker estimator depends on turn rate of tanker for locating a rendezvous point based on tanker states and UAV states
\[ \dot{\psi}_{com} = -\lambda_1 \dot{\phi} \quad \text{where} \quad \dot{\phi} = \frac{d(\Phi_f - \theta)}{dt} = \frac{(\dot{x}_R - \dot{y}_T)(x_R - x_T) - (\dot{x}_R - \dot{y}_T)(y_R - y_T)}{s^2} \]

and

\[ s = \sqrt{(X_{I,R} - X_{I,T})^2 + (Y_{I,R} - Y_{I,T})^2} \]

assuming

\[ \dot{x}_T = 0, \quad \dot{y}_T = 0 \]

Note different definitions for heading and LOS orientation

S is range-to-go

Phi final is a function of final heading constraint
Initially...

\[ \lambda_1 = \frac{-(\Psi_f - \psi)}{\Phi_f - \phi} \quad \text{or} \quad \dot{\psi}_{\text{com}} = \dot{\psi}_{\text{max}} \text{sgn}(\Phi_f - \phi) \]

\[ \lambda_1 > 1 \Rightarrow s \to 0 \]
\[ \lambda_1 > 2 \Rightarrow \Phi_f = -\frac{\pi}{2} - \Psi_f \]

Guidance Law Properties

Adaptation...

\[ \dot{\lambda}_1 = -\frac{\kappa}{s^2} \left( \lambda_1 + \frac{\Delta\psi}{\Delta\phi} \right) \left( x_R\dot{x}_R - x_T\dot{x}_T + (y_R\dot{y}_R - y_T\dot{y}_T) \right) \]

where...

\[ \Delta\psi = \Psi_f - \psi \]
\[ \Delta\phi = -\left( \Psi_f + \frac{\pi}{2} \right) - \phi \]
\[ \kappa = \text{constant gain} \]

An initial PN gain calc is made, it must be greater than two to guarantee the final heading constraint is met, if it is not >2, then the aforementioned turn rate command is used, which will eventually increase the PN gain above 2.

Adaptation ensures final heading constraint is met even when: guidance commands exceed maneuverability of vehicle (alg uses kinematics), limits are saturated, movements in the target caused by tanker drift, winds, etc.

Final LOS angle definition ensures receiver will approach tanker from behind as it nears its final heading.
Guidance Law
Velocity Controller

\[ A_{com} = -k_1 \left( \frac{V_R - \frac{t_R + 1}{t_T + 1} V_T}{s} \right)^2 \text{sgn}(V_R - \frac{t_R + 1}{t_T + 1} V_T) \]

\[ \frac{t_R + 1}{t_T + 1} = \text{time-to-target ratio} \]
- Increases or decreases target velocity
- Neither \( t_R \) or \( t_T \) is a guess of the RZ time or the actual time of arrival to target
- The ratio gives a relative sense of how far ahead or behind the tanker the UAV is from the target RZ location

\( (t_R + 1)/(t_T + 1) \to 1 \) as Receiver and Tanker approach RZ

Time-to-Target ratio is receiver time-to-target over tanker time-to-target

Less than one, receiver slows down; greater than one, receiver speeds up
Results

• Simulation
  - 6DOF Tanker and UAV models
  - Tanker
    • $\psi_{t=0}=0^\circ$
    • $V=670\text{ft/s}$
  - UAV
    • $V_{t=0}=750\text{ft/s}$
  - Wind

• UAV Limits
  • $\pm 2\text{ deg/s}$ turn rate
  • $\pm 2\text{ ft/s}^2$ accel/decel
  • 600-800 ft/s V range

*Everything not listed is variable*
Results

$\Psi_{t=0}=90^\circ$, no wind, $P_{t=0}=(-40000,15000)$ ft

-Tanker flying straight leg
Results

- Velocity (V) vs. Time (t)
- Range (NM) vs. Time (t)
- Heading Angle (Psi) vs. Time (t)

(Charts showing trends and data points from t=0 to t=250, with specific values for V, Range, and Psi indicated.)
Results

$\Psi_{t=0}=110^\circ$, no wind, $P_{t=0}=(-50000,30000)$ ft

- Tanker turns with $15^\circ$ bank at $t=30s$
**Results**

Turn rate saturated, Receiver crosses tanker path, but comes back around and hits RZ location (but well behind tanker)
Crossing path behind tanker presents a problem with guidance law because phi - phi -> 0, but RZ is not occurring...logic was introduced to handle this
Results

$\Psi_{t=0}=90^\circ$, Wind SE @ 50KT for 100s, $P_{t=0}=(-40000,15000)$ft

-Tanker flying straight leg
Results

This has both a PN gain re-initialization and winds that test the adaptation. Sequence of target locations reflects tanker maneuver and wind effects.
Results

$\Psi_{t=0}=70^\circ$, Wind SE @ 50KT for entire sim, $P_{t=0}=(-40000,15000)$ft

- Tanker turns with $15^\circ$ bank at $t=30s$
Results
Discussion and Conclusion

• PN with adaptive terminal guidance is shown to be a viable guidance method for aircraft rendezvous in 6DOF simulation
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References

