Proposal

Terminal Guidance for Autonomous Aerial Refueling

Submitted for the
Undergraduate Research Scholarship Competition

by

Nicholas S. Higgins
153 E 14th Avenue
Columbus, Ohio 43201

Advisor: Clifford A. Whitfield, Ph. D.

October 29, 2010

Introduction

Unmanned Aerial Vehicles (UAVs) are used to provide services within the U.S.DoD components – services that can sometimes be considered too “dull, dirty, or dangerous” for manned aircraft. The central areas, ‘dull’ (Intelligence, Surveillance, and Reconnaissance ISR), ‘dirty’ (atmospheric environment assessment), and ‘dangerous’ (suppression of enemy air defense) are tasks that UAVs can accomplish within military and civilian arenas. The U.S. Military categorizes each UAV based on the vehicle’s mission capability and performance characteristics using a tier system. Each military branch has separate parameters within the tier systems, but the concepts for categorization are similar. Micro or small UAVs, such as the RQ-14 Dragon Eye, operate at low Tier I altitudes. The second tier, Tier II, are vehicles that fly at mid-range altitudes and can typically operate for 14 to 28 hours, unrefueled. Examples of Tier II vehicles include the MQ-1 Predator, MQ-9 Reaper, and the ScanEagle. UAVs within the Tier III category operate at altitude at or above 60,000 feet. An example of a Tier III vehicle is the RQ-4 Global Hawk, which has an endurance of 36 hours at an altitude of 65,000 feet.

As missions become longer and travel distances further, it becomes challenging for UAVs to stay fueled while in flight. For example, requirementsare being considered for UAVs to travel overseas instead of being shipped in parts and rebuilt. For Tier II and Tier III UAV operations, using conventional fuel systems causes the vehicle to be limited in range and duration based on its fuel load. Air refueling tankers extend these capabilities for tactical manned Navy aircraft; however, for unmanned aircraft, UAVs currently lack in-flight capability of docking a refueling probe to the tanker, autonomously.

There are two types of common hardware configurations and methods for aerial refueling – boom-and-receptacle and probe-and-drogue. A boom-and-receptacle configuration requires the receiving aircraft to maintain position with respect to the refueling tanker as the refueling boom is extended and steered from the tanker to the vehicle. In a probe-and-drogue configuration, the tanker trails a refueling drogue, an aerodynamically stable basket, and the vehicle to be refueled extends a probe which is flown into the basket. This technique is currently the standard aerial refueling configuration for the U.S. Navy and the air forces of most nations. An advantage to this method is the fact that it does not require a human operator on-board the tanker, as does the boom-and-receptacle configuration. Also, another advantage of the probe-and-drogue over the boom-and-receptacle is the physical flexibility of the refueling hose and drogue. This physical flexibility allows the drogue to be essentially passive during refueling, allowing the receiving aircraft to be uninhibited while behind the tanker– a crucial necessity for small and agile aircraft such as Tier II UAVs. Figure 1 is a diagram of the probe-and-drogue configuration.

Objective

Autonomous UAV technology exists and is commonly used in open airspace flight. However, technology is limited when flying within close quarters of an air refueling tanker. The area behinda tanker requires terminal guidance capability, where the wake effects from the tanker's wing can cause the air behind the wing to be highly unstable. A diagram of this description is presented in Figure 2.

In order for UAVs to achieve in-flight refueling, the terminal guidance of Autonomous Aerial Refueling (AAR) for UAVs must be developed. Equipping a UAV with the resources for AAR requires terminal guidance technology capable of providing accurate real-time location and orientation measurements of the UAV refueling probe relative to the drogue; and the autonomous capability to successfully dock. UAV-autonomy technologies fall under the following categories[1]:

- *Sensor fusion* – combining information from different sensors for use on-board the vehicle
- *Communications* – handling communications and coordination between multiple agents in the presence of incomplete and imperfect information
- *Path planning* – determining an optimal path for the vehicle to go while meeting certain objectives and mission constraints such as obstacles or fuel requirements
- *Trajectory generation* (sometimes called *Motion planning*) – determining an optimal control maneuver to take to follow a given path or to go from one location to another
- *Trajectory regulation* – the specific control strategies required to constrain a vehicle within some tolerance to a trajectory
- *Task allocation and scheduling* – determining the optimal distribution of tasks amongst a group of agents, with time and equipment constraints
- *Cooperative tactics* – formulating an optimal sequence and spatial distribution of activities between agents in order to maximize chance of success in any given mission scenario

In order for a successful rendezvous, the UAV must have trajectory generation and regulation capability through sensor fusion and task allocation in close proximity to obtain docking with the drogue.

The proposed research is to develop terminal guidance for UAV-AAR capability. For this proposal, it has been determined to use a refueling probe and drogue configuration for the development of terminal guidance for aforementioned reasons.

Methodology

The proposed method for developing UAV-AAR terminal guidance will use trajectory regulation control methodology along withthe Dual-Optimal Path-Planning (D-O.P-P.) Technique as defined by Whitfield[1]. The D-O.P-P. Technique is an adaptive on-line multi-objective technique for UAV path and trajectory generation through task allocation and sensor fusion. The technique will allow the UAV to adapt to the unsteady nature of aerial refueling while determining an optimum path to achieve successful docking. The technique, in general form, can be expressed mathematically and shown in Table 1. This technique utilizes dynamic optimization for determining optimal flight trajectories between continually updating optimal intermediate-states for the UAV, based on environmentally-influenced objectives; and is summarized below.

The environmentally-influenced optimal condition, known as the ‘driver,’ determines the next condition, within a downstream virtual window of possible vehicle destinations and orientation built from the UAV kinematics. This sequential optimization technique is a multi-objective optimization procedure consisting of two goals. The individual goals and their objective difficulty are not limited in type and are determined on an individual basis. The solving technique is also algorithm independent, allowing for adaptability in the process of developing the vehicle trajectory. The vehicle’s initial location $\mathbf{x}_{k\text{-}1}$($\mathbf{x}^*_{k\text{-}1}$ for an optimum) for 2-D flight consists of its location, velocity, bank angle, and heading, and is given in the following relationship: $f(\mathbf{x}_{k\text{-}1}) = f(x_{k\text{-}1}, y_{k\text{-}1}, V_{k\text{-}1}, \phi_{k\text{-}1}, \psi_{k\text{-}1})$. In terms of three dimensional, the vehicle’s pitch angle and altitude are also required. At the initial location with the driver window projection distance, the available UAV flight window is projected forward of the heading direction andbounded based on the vehicle's kinematics.In the case for the terminal guidance of UAV-AAR flight, the drogue is the final destination (k = N).

UAV-AAR Implementation

In order to apply the D-O.P-P. Technique to UAV-AAR, the requirements and constraints must be identified. AU.S. fuel-based Tier II UAVwill be determined for this research and selected using the *AIAA 2009 Worldwide UAV Roundup*[2]. After selecting a Tier II UAV, its stability and controllability kinematicsas well as aerodynamic performance characteristics will be obtained and computationally modeled.A C-130 Hercules refueling tanker wing's wakedistribution will be experimentally gathered for the UAV-AAR computational investigations using a 1/24th scale half-span model tested in the 3'x5' Subsonic Wind Tunnel facility at the Ohio State University Aeronautical and Astronautical Research Laboratory.

Investigations of potential transmitting equipment, visual and non-visual, capability, versatility, and adaptability will be continued; and equipment selected to be used as operational requirements and limitations for developing the terminal guidance of UAV-AAR. Transmitting equipment will be located on or near the drogue unit, transmitting its location to the UAV.

Using the selected Tier II UAV flight characteristics, fuel-tanker wing wake distributions, and existent transmitting and receiving equipment capabilities, representative flight simulations will be flown and results analyzed, demonstrating its capability to provide terminal guidance to UAV-autonomy in aerial refueling.

References

1. Whitfield, C.A., “An Adaptive Dual-Optimal Path-Planning Technique for Unmanned Air Vehicles with Application to Solar-Regenerative High Altitude Long Endurance Flight,” The Ohio State University, 2009.

2. “2009 Worldwide UAV Roundup,” AIAA, <www.aiaa.org>

3. Fravolini, M.L., Ficola, A., Giampiero C., Napolitano, M.R., Seaonr, B. “Modeling and Control Issues for Autonomous Aerial Refueling for UAVs Using a Probe-Drogue Refueling System,” Aerospace Science & Technology, Vol. 8, 2004, pp. 611-618.

4. Tandale, M.D., Bowers, R., Valsek, J. “Trajectory Tracking Controller for Vision-Based Probe and Drogue Autonomous Aerial Refueling,” Journal of Guidance, Control, and Dynamics, Vol. 29, No. 4, July-August 2006.

5. Various authors “Unmanned Aerial Vehicle,” Wikipedia, <http://en.wikipedia.org/wiki/UAV>

6. Nelson, R. “Flight Stability and Automatic Control,” The McGraw-Hill Companies, Inc., Boston, 1998.

7. Sattigeri, R.J., Johnson, E., Calise, A.J., Ha, J., “Vision-based Target Tracking with Adaptive Target State Estimator,” AIAA Guidance, Navigation and Control Conference and Exhibit, Hilton Head SC, 20-23 August 2007.

8. Arora, J.S., “Introduction to Optimum Design,” Elsevier Academic Press, San Diego CA, 2004.

9. Bryson, A.E. Jr. “Dynamic Optimization,” Addison-Wesley Longman Inc., Menlo Park CA, 1999.

10. Bryson, A.E. Jr., Ho, Y-C. “Applied Optimal Control: Optimization, Estimation, and Control,” Taylor and Francis Group, New York, NY, 1975.

11. Cloud Cap Technology, Piccolo Highly Integrated Autopilots, <http://www.cloudcoptech.com/piccolo_system.shtm>

12. Wang, J., Patel, V.V., Cao, C., Hovakimyan, Lavretsky, E.N. “Novel L_1 Adaptive control Methodology for Aerial Refueling with Guaranteed Transient Performance,” Journal of Guidance, Control, and Dynamics Vol. 31, No. 1, January-February 2008.

13. Valasek, J., Gunnam, K., Kimmett, J., Tandale, M.D., Junkins, J.L., and Hughes, D., “Vision-Based Sensor and Navigation System for Autonomous Air Refueling,” Journal of Guidance, Control, and Dynamics, Vol. 28, No. 5, Sept.-Oct. 2005, pp. 832-844.

List of Figures

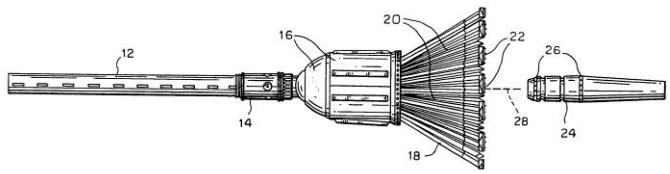

Figure 1: Proposed Probe-Drogue Design

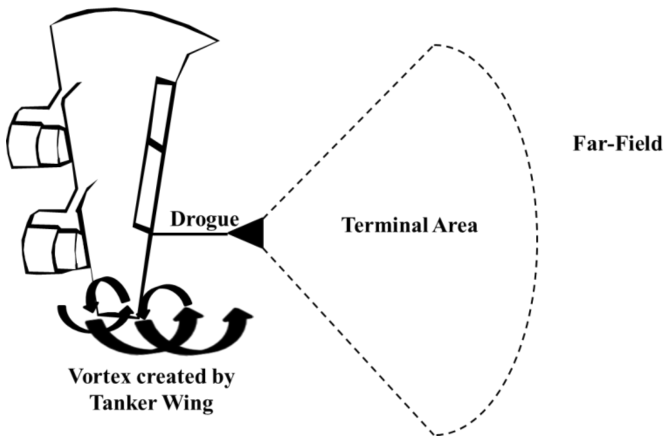

Figure 2: Terminal Area Diagram

Table 1: Dual-Optimal Path-Planning Technique – General Form

Driver:

$$\textit{Minimize } f(\mathbf{x}); \quad \textit{subject to } g_i(\mathbf{x}), (i = 1, \dots, n),$$

with solution:

$$\mathbf{x}_k^*, (k = 1, \dots, N)$$

Path:

$$\textit{Minimize } J(u) = \int_0^T f_0(\mathbf{x}(t), u(t))dt,$$

where

$$\mathbf{x}(t), (\mathbf{x}_{k-1}^*(t), \dots, \mathbf{x}_k^*(t)): \quad [0, T] \to \Re^n$$

is the solution of the differential system with boundary conditions and with initial and final conditions

$$\frac{d\mathbf{x}_j}{dt} = f_j(\mathbf{x}, u(t)), \quad (j = 1, \dots, n);$$

$$\mathbf{x}(0) = \mathbf{x}_{k-1}^*; \quad \mathbf{x}(T) = \mathbf{x}_k^*$$

where

$$J(u^*) = \min_{u \in U} J(u)$$

with u^* *and the associated path* $\mathbf{x}$ *called 'optimal.'*