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A Survey of the Dynamics and Control of Aircraft During Aerial Refueling

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Abstract: Recent heightened interest in autonomous refueling of unmanned aerial vehicles has stimulated research activity in the area of aerial refueling in general. Aircraft aerial refueling research can be divided into four general areas: influence of tanker aircraft wake turbulence on the receiver aircraft, the dynamics of the drogue and hose, automatic flight control system design for aerial refueling, experiments and flight tests related to the practical implementation of autonomous aerial refueling system. This survey summarizes research activities as well as the current state of knowledge in these areas.

Keywords: *Aerial refueling; variable mass system; aircraft dynamics.*

Mathematics Subject Classification (2000): 93C20, 93C35, 93C85.

1 Introduction

Aerial refueling is the practice of transferring fuel from one aircraft to another during flight. It allows the receiving aircraft to remain airborne longer, and to take off with a greater payload. Aerial refueling operation with manned aircraft has been implemented by many countries since after the Second World War. In-flight refueling was first proposed in 1917 by Alexander P. de Seversky, who was then a pilot in the Russian Navy. The motive was to increase the range of combat aircraft. De Seversky soon emigrated to the United States and became an engineer in the War Department. He initiated work on Aerial Refueling in the United States. Although experiments in aerial refueling started as

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early as the 1920s, hardly any analytical study in this area of research was conducted until the 1980s. The purpose of this paper is to give an overview of research work conducted to date on in-flight refueling of flight vehicles.

Early research work on aerial refueling concentrated on the aerodynamics aspect of aerial refueling, mainly the influence of the tanker wake turbulence on the stability and control of the receiver aircraft. In recent years, more and more Unmanned Air Vehicles (UAVs) are used in military operations. As UAVs are expected to perform functions similar to those of manned aircraft, UAVs are also expected to have an aerial refueling capability. This expectation has motivated much of recent research work on aerial refueling. The ultimate goal of aerial refueling research is to develop reliable automatic flight control systems which can guide UAVs or manned aircraft through aerial refueling operation.

2 Aerial Refueling Methods

There are two methods commonly used for aerial refueling: Probe and Drogue Refueling (PDR) and Boom and Receptacle Refueling (BRR). In the probe and drogue method, the tanker aircraft releases a long flexible hose that trails behind and below the plane. At the end of the hose is a cone-shaped component known as a drogue or basket. A plane that needs to refuel extends a device called a probe, which is a rigid, sometimes jointed, arm placed usually on one side of the airplane. As the tanker flies straight and level with no control on the drogue, the pilot of the receiving aircraft flies his airplane behind and below the tanker aircraft and in such a way that the probe mounted on the receiver aircraft links up with the drogue from the tanker. Once the connection is made, a valve in the drogue opens to allow fuel to be pumped through, and the two aircrafts fly in formation until the fuel transfer is complete. The receiver aircraft then decelerates hard enough to pull the probe out of the basket. PDR is the standard aerial refueling procedure for the US Navy (USN), North Atlantic Treaty Organization (NATO) nations, Russia, and China.

In the boom and receptacle refueling method, the boom is a long, rigid, hollow shaft, usually fitted to the rear of the tanker aircraft. It normally has a telescoping extension, a valve at the end to keep fuel in and permit it to flow when necessary, and small wings to enable it to be "flown" into a receptacle of the aircraft to be refueled. The plane that is to receive fuel is equipped with a receiver socket fitted onto the top of the aircraft, on its center line and usually either behind or close to the front of the cockpit. The receiver socket is a round opening which connects to the fuel tanks, with a valve to keep the fuel in when the plane is not being refueled, and dust and debris out. The boom has a nozzle which fits into this opening. During refueling operations, the tanker aircraft flies in a straight and level attitude at constant speed, while the receiver takes a standard position behind and below the tanker. As the receiver pilot flies in formation with the tanker, the boom operator in the tanker's tail uses a joystick to move the boom and extend the telescoping component to connect the boom's nozzle to the receiver. When an electrical signal is passed between the boom and receiver, the valves in both the boom and the receiver are opened. Pumps on the tanker drive fuel through the boom's shaft and into the receiver. When refueling is complete, the valves are closed and the boom is retracted. BRR is the preferred refueling method for the US Air Force (USAF). In addition to the US Air Force, BRR is also used by the Netherlands, Israel , Turkey, and Iran.

Compared to BRR, PDR is simpler and more flexible in its implementation. Many types of aircraft can be modified to carry drogue systems. The PDR system allows multiple aircraft being refueled simultaneously, and requires no extra boom operator. However, PDR relies on the receiver aircraft to make the refueling connection, which can be a demanding task especially for a fatigued pilot or during night/bad weather operations. PDR also provides a lower fuel transfer rate in general. In BRR, the receiver pilot's workload is slightly lower, and BRR also provides higher fuel transfer rate. However, the tanker can only service one receiving aircraft at a time. The space and weight associated with the boom assembly puts a restriction on the types of aircraft that can be equipped with this system.

An aerial refueling procedure can be divided into three phases: the pre-refueling or approach phase, the refueling phase, and the separation phase. In the approach phase, the receiver aircraft approaches the tanker aircraft from below and behind and gets connected with the tanker. During the refueling phase, fuel is pumped from the tanker aircraft into the receiver aircraft. The receiver aircraft tries to hold a stationary position relative to the tanker aircraft to maintain the connection between drogue and probe, or boom and receptacle. This phase can also be called the station keeping phase. The separation phase begins as soon as fuel transfer ends. The receiver aircraft decelerates and becomes detached from the tanker aircraft.

Flying the receiver aircraft during aerial refueling, especially during the first two phases, is much more difficult than under normal flight condition because of tanker wake turbulence. Furthermore, as the receiver aircraft approaches the tanker aircraft in PDR, the relative position of the hose and drogue fluctuates due to wind gusts and turbulence. It is not a trivial task to make the connection between the drogue and the probe. For a manned aircraft, such difficulties can be overcome by a pilot's agility. For UAVs, these difficulties impose challenges that must be resolved through automatic flight control system design.

3 Aerodynamic Effects on the Receiver Aircraft

Although practical attempts at aerial refueling started in the 1920s, there was little theoretical research work related to aerial refueling until the 1980s when the needs of simulation software for pilot training made it necessary. One of the first questions to be addressed by researchers is whether the aerodynamic impact of the tanker wake turbulence on the receiver aircraft is significant.

Bloy et al [6] studied the lateral dynamic stability and control of a large receiver aircraft during aerial refueling in 1986. The probe and drogue refueling approach was assumed in the study. The receiver aircraft was taken to be at a typical refueling location approximately two wing spans directly behind and a quarter wing span below the tanker aircraft. In the study, a simple horseshoe vortex model was assumed for the tanker vortex field. Due to the effect of the tanker vortex field, two additional derivatives were found to be required for studying the dynamics of the receiver. These derivatives are the rolling moment due to bank and the rolling moment due to sideways displacement. It was found that these derivatives are both negative, which means that the receiver aircraft is statically stable with respect to lateral displacement and bank attitude. To study the lateral dynamic stability of the receiver aircraft, the linearized lateral equations of motion for initially steady, straight, horizontal flight were used. These equations were then written in the generalized Eigenproblem form $Ax = \lambda Bx$, and dynamic modes were calculated. The receiver aircraft was found to exhibit divergent oscillations involving mainly bank and sideways displacements under the influence of the tanker vortex field.

Bloy et al [3] extended their work to the study of the longitudinal dynamic stability and control of a large receiver aircraft during aerial refueling in 1987. The assumptions are the same as those in the previous study. For the dynamics of longitudinal motion, the two most important additional aerodynamic derivatives were the normal force due to vertical displacement and the pitching moment due to vertical displacement. These two derivatives were found to be negative, which means that the receiver is statically stable with respect to steady state. The linearized longitudinal equations of motion were derived, and were used to show that the receiver aircraft exhibits instability or near neutral stability in vertical displacement depending on the relative values of the mean span-wise downwash gradients at the receiver wing and tail-plane positions.

Bloy et al [8] further studied the longitudinal stability of receiver aircraft for different aerial refueling configurations. Two receivers, the VC10 and Hercules, were refueled from four tanker aircrafts, Victor, Hercules, VC10, and Tristar. It was found that the receiver aircraft longitudinal stability depends on several parameters: the vertical separation between the receiver and the tanker, tanker properties (wing-span and weight which all affect the vortex field produced), receiver properties (tail-plane height, mass, center of gravity position), flight speed, and attitude of aircraft. Among the parameters, the most important appeared to be the vertical separation between the receiver and the tanker. The vortex field at the receiver aircraft position varies with the separation distance. Thus, the drag and lift caused by the vortex field also change. Furthermore, the relative downwash at the wing and tail-plane of the receiver also changes, and this causes variation in the pitch moment on the receiver.

To verify their theoretical results, Bloy et al [9] conducted wind tunnel experiments with models of tanker and receiver aircraft. The tanker was modeled as a straight wing while the receiver aircraft was modeled as a wing and fin with tail-plane at low, medium, or high positions. Both the tanker model and the receiver model were put into a wind tunnel with relative position similar to that in aerial refueling. The aerodynamic forces and moments acting on the models were measured and compared with those obtained from theoretical computation. The experimental results were found to be in fairly good agreement with the theoretical predictions. Bloy et al further extended their wind tunnel experiments on tanker models with the use of a flapped wing [10] and a tapered wing [12, 7]. In these later cases, the theoretical and experimental trends were similar, although there were significant differences between theory and actual experimental data due presumably to wind tunnel boundary interference effects.

To consider the effect of different vortex models, a flat vortex sheet model and a more realistic roll-up vortex model were compared for the tapered tanker wing [11]. For the flat vortex model, the downwash over the central part of the receiver wing is less than that obtained from the wake model with roll-up. Towards the tip, the situation is reversed. The effect of wake roll-up on receiver rolling moment due to sideways displacement derivative was also calculated and compared with that for the flat vortex model. The wake roll-up model showed much higher rolling moment values from the comparison.

The studies of Bloy et al [6, 3, 8, 9, 10, 12, 7, 11] indicate that a tanker aircraft's wake turbulence has a significant impact on the receiver aircraft's dynamics. The subsequent question is how the influence of tanker wake turbulence should be accounted for in analytical studies and simulations. One approach is to consider the variable downwash and sidewash distribution of tanker wake turbulence on the lifting surfaces of the receiver aircraft, and determine the resultant aerodynamic forces and moments on the receiver aircraft using complicated computational fluid dynamics models. This method is called the exact model method. To ensure accuracy, computational predictions from such models are often verified with wind tunnel experiments. Blake et al [2] presented results from a wind tunnel testing of Innovative Control Effectors 101 (ICE101), a tailless aircraft configuration, behind a KC-135R tanker, and compared these results with predictions from a planar vortex lattice code. The aircraft models were 1/3 scale, and they were tested in a full scale wind tunnel. The KC-135R wake induced lift, drag, pitching moment, rolling moment, yawing moment and side force on ICE101 with different relative vertical and lateral positions were measured and compared with predictions from the planar vortex lattice model. Both the predictions and measured data show wake interference effects that vary significantly with relative lateral and vertical position, and weakly with relative longitudinal position. Results from wind tunnel tests and theoretical predictions were found to be in excellent agreement except for drag. The discrepancy in the drag results is believed to be due to the fact that viscous effects are ignored in the vortex lattice model.

Predicting aerodynamic forces and moments with an exact model method is computation intensive. A simpler method is to only consider the tanker wake conditions at the receiver's center of gravity, to assume linear distributions of downwash and sidewash on receiver aircraft lifting surfaces, and determine the resultant aerodynamic forces and moments. This method is called the single-point model method. In this method, calculations are greatly simplified. Bloy et al [4] proposed and validated the single-point model method for aerial refueling simulations. They found out that the single point method is adequate whenever the ratio of the wing span of the receiver aircraft to that of the tanker aircraft is much less than one. The method becomes less accurate as the wing span of the receiver aircraft is increased. The benefit of the single-point model is that it does not demand extensive computation, which is good for real time analysis.

Venkataramanan and Dogan [33, 16] developed another approximate method for the calculation of aerodynamic coupling between two aircraft flying close to each other, as is the case during aerial refueling. In the method proposed, the average wind velocity and the weighted average of wind velocity gradient on the surface of the trailing aircraft is taken to be the effective wind velocity and wind velocity gradient acting on the center of gravity of the aircraft. Svoboda and Ryan [29] developed an aerodynamic model of Boeing E-3A based on models of aerial refueling between two tankers, Boeing KC-135R and Douglas KC-10A, and five receivers, Lockheed C-141B, Lockheed C-5B, Douglas C-17A, Douglas KC-10A, and Boeing KC-135R. To establish the aerodynamic models of aerial refueling between these tankers and receivers, free air simulation and free air flight test were performed first and data collected. Then, flight test data were collected during aerial refueling. The effects of the tanker wake turbulence on the receiver were found out by comparing the difference between free air flight test data and aerial refueling flight test data. Simulation models for aerial refueling between these tankers and receivers were obtained from the comparison. As the configuration of Boeing E-3A is similar to Douglas DC-10A and Boeing KC-135R, the authors assumed that the aerial refueling model of Boeing E3A is an average of those for Douglas DC-10A and Boeing KC-135R.

In recent years, much research effort is focused on the development of autonomous aerial refueling of UAVs. Clearly, aerodynamic models for UAVs are required for this purpose. To protect proprietary data of different combat UAV manufacturers (Boeing and Northrop Grumman), an equivalent simulation model was developed [1] at the Air Force Research Laboratory (AFRL). This model allows simulation research and development to be conducted for automated aerial refueling of unmanned aerial vehicles. The

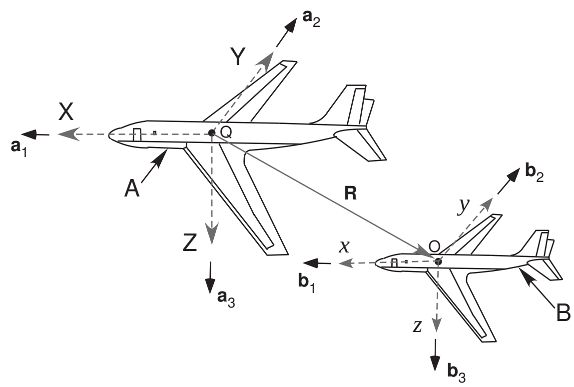

Figure 4.1: Aerial refueling.

model is developed based on ICE 101, whose configuration and aerodynamic data had been cleared for release to the public. Specifications independently provided by Boeing, Northrop Grumman, and a special design team at AFRL are combined to yield non-proprietary specification for the equivalent model. The physical, aerodynamic, and control characteristics of ICE 101 are then modified to satisfy the specifications. This modified model of ICE 101 is intended to be used for UAV automated aerial refueling research.

4 Effects of Mass Variation on the Dynamics of Receiver Aircraft

F. Eke and W. Mao [22] extend the study of dynamics of variable mass system [18, 17, 27, 34] to the dynamics of receiver aircraft during aerial refueling (Figure 4.1). In their study, the translational motion and rotational motion of the receiver aircraft are described by the following two equations.

$$\begin{aligned}\mathbf{F}_G + \mathbf{F}_E + \mathbf{F}_A \;=\;& (M_B + m_F)\Big[{}^N\mathbf{a}^Q + \ddot{\mathbf{R}} + 2\,{}^N\boldsymbol{\omega}^A \times \dot{\mathbf{R}} \\ &+ {}^N\boldsymbol{\alpha}^A \times \mathbf{R} + {}^N\boldsymbol{\omega}^A \times \left({}^N\boldsymbol{\omega}^A \times \mathbf{R}\right)\Big] \\ &+ m_F\left\{\left({}^N\boldsymbol{\alpha}^A + {}^A\boldsymbol{\alpha}^B + {}^N\boldsymbol{\omega}^A \times {}^A\boldsymbol{\omega}^B\right) \times \mathbf{r}_F^* \right.\\ &\left.+ \left({}^N\boldsymbol{\omega}^A + {}^A\boldsymbol{\omega}^B\right) \times \left[\left({}^N\boldsymbol{\omega}^A + {}^A\boldsymbol{\omega}^B\right) \times \mathbf{r}_F^*\right]\right\} - \dot{m}_F \mathbf{v}_r\end{aligned} \tag{1}$$

and

$$\begin{aligned}\mathbf{M}_G + \mathbf{M}_E + \mathbf{M}_A \;=\;& m_F \mathbf{r}_F^* \times \Big[{}^N\mathbf{a}^Q + \ddot{\mathbf{R}} + 2\,{}^N\boldsymbol{\omega}^A \times \dot{\mathbf{R}} \\ &+ {}^N\boldsymbol{\alpha}^A \times \mathbf{R} + {}^N\boldsymbol{\omega}^A \times \left({}^N\boldsymbol{\omega}^A \times \mathbf{R}\right)\Big] \\ &+ (\mathbf{I}_B + \mathbf{I}_F)\cdot\left({}^N\boldsymbol{\alpha}^A + {}^A\boldsymbol{\alpha}^B + {}^N\boldsymbol{\omega}^A \times {}^A\boldsymbol{\omega}^B\right) \\ &+ \left({}^N\boldsymbol{\omega}^A + {}^A\boldsymbol{\omega}^B\right) \times (\mathbf{I}_B + \mathbf{I}_F)\cdot\left({}^N\boldsymbol{\omega}^A + {}^A\boldsymbol{\omega}^B\right) \\ &+ \left(\frac{{}^B d\mathbf{I}_F}{dt}\right)\cdot\left({}^N\boldsymbol{\omega}^A + {}^A\boldsymbol{\omega}^B\right) - \dot{m}_F \mathbf{r}_R \times \mathbf{v}_r \\ &- \dot{m}_F \mathbf{r}_R \times \left[\left({}^N\boldsymbol{\omega}^A + {}^A\boldsymbol{\omega}^B\right) \times \mathbf{r}_R\right],\end{aligned} \tag{2}$$

where $\mathbf{F}_G$, $\mathbf{F}_E$, $\mathbf{F}_A$ are gravity force, thrust, and aerodynamic force respectively; $\mathbf{M}_G$, $\mathbf{M}_E$, $\mathbf{M}_A$ are moment due to gravity force, engine's angular momentum, and aerodynamic moment respectively; M_B is the mass of receiver aircraft without fuel, m_F is the mass of fuel, $\mathbf{R}$ is the position vector of the receiver aircraft relative to the tanker aircraft, $\mathbf{r}_F^*$ is the position vector of fuel mass center in receiver's body frame, ${}^N\mathbf{a}^Q$ is the acceleration of the origin of the tanker's body frame, ${}^N\boldsymbol{\omega}^A$ is the angular velocity of the tanker aircraft relative to an inertia frame, ${}^N\boldsymbol{\alpha}^A$ is the angular acceleration of the tanker aircraft relative to an inertia frame, ${}^A\boldsymbol{\omega}^B$ is the angular velocity of the receiver aircraft relative to the tanker aircraft, ${}^A\boldsymbol{\alpha}^B$ is the angular acceleration of the receiver aircraft relative to the tanker aircraft, $\mathbf{v}_r$ is the fuel velocity at entry point relative to the receiver's body frame, $\mathbf{r}_R$ is the position vector of the fuel entry point relative to the receiver's body frame, $\mathbf{I}_B$ is the moment of inertia of the receiver aircraft without fuel, $\mathbf{I}_F$ is the moment of inertia of the fuel.

Results obtained from numerical simulations indicate that mass variation due to fuel transfer compounds the difficulties created by tanker wake turbulence. In order to keep the receiver aircraft at a fixed position relative to the tanker during aerial refueling, appreciable adjustments must be made to the receiver's angle of attack, throttle setting and elevator deflection. A larger refueling rate demands even larger adjustments. Changes in certain other parameters related to aerial refueling can also amplify the effects of mass variation on the receiver motion, or influence the system's dynamics in other ways.

5 Dynamics of Drogue and Hose

During air-to-air refueling with the hose and drogue approach, the hose and drogue trail down from a tanker aircraft. The hose and drogue are subject to aerodynamic forces, gravity, and tension. The vortex field of the tanker aircraft and the receiver aircraft nose, when the receiver is close enough, also have an impact on the hose and drogue. A good understanding of the dynamics of the hose and drogue makes the position of the drogue more predictable, which is important to the aerial refueling procedure. Bloy et al [5] proposed a static model of hose and drogue. They found that the motion of the drogue is well damped and the interference effect of the receiver nose on the drogue can be determined to satisfactory accuracy from the static analysis of the hose and drogue when the receiver aircraft approaches at a typical closure speed used in aerial refueling. In their study, finite element analysis was applied to the hose. A hose element is subject to the aerodynamic force on the element, gravity, and tension forces at two ends. Equilibrium equations can be written for the hose element. For all the hose elements, a set of equations can be obtained. Similarly, equilibrium equations can be written for the drogue. All these equations can then be solved iteratively to obtain the displacement of the end points of each element.

Researchers at NASA Dryden Flight Research center [31] used experimental methods to support the development of accurate aerodynamic models of the drogue and hose assembly to be used in refueling simulations. In flight tests, the thrust of the tanker aircraft was measured. The difference in the thrust measured when the drogue and hose were deployed and when they are stowed is attributable to the drag of the drogue and hose. Drag data were obtained at different airspeed and altitude. It was found that drag increases linearly with airspeed, but that there was no discernible altitude effect on drag. When the receiver airplane engaged the drogue, some of the aerodynamic load (drag) on the drogue and hose assembly was transferred from the tanker to the refueling probe of the receiver. There is also a linear trend in such drag relief as airspeed increases. Data obtained from flight tests were compared with wind tunnel results, and they were in good agreement.

Hansen et al [20] hypothesized that the position of the drogue relative to the tanker is a function of several independent variables and could be obtained by the superposition of the constituent effects. The variables considered are flight condition, drogue condition, hose weight effects, tanker effects, and receiver effects. Flight tests with two F/A-18 were designed to determine the change in drogue position as a function of individual influences. One of these two F/A-18 aircraft carried the aerial refueling store (ARS), and performed as the tanker, and the other F/A-18 acted as the receiver. Cameras were mounted on both aircrafts to monitor and measure the position and the movement of the drogue. Several effects on the hose and drogue were observed during the flight tests.

1. Free-Stream Drogue Position and Airspeed: It is observed that the drogue position is higher with faster tanker airspeed.

2. Free-Stream Drogue Position and Tanker Angle of Attack (AOA): As AOA increases, the drogue position becomes lower almost linearly.

3. Free-Stream Drogue Position and Turbulence: In light turbulence, the drogue did not stabilize; it randomly meandered in the horizontal and vertical directions by as much as a drogue diameter (approximately 0.6m).

4. Area of Influence (AOI): As the receiver approaches the drogue, the nose of the receiver has a measurable effect on the drogue position. The boundary of the AOI is defined by the locus of points at which the nose of the receiver has a minimum measurable effect on the drogue position.

Valuable data have been collected from flight tests [20, 31], and more flight tests have been planned for the complete modeling of the hose and drogue dynamics.

6 Automatic Flight Control System

Automatic flight control system (FCS) design for aerial refueling involves the selection of sensors for detecting the relative position of the tanker aircraft and the receiver aircraft, as well as the development of control laws to guide the aerial refueling process.

Valasek et al [32] proposed the use of an optical sensor fixed on the tanker aircraft to detect the position of the drogue. Several LED based beacons are attached to the drogue. Analysis of signals sent between the beacons and the optical sensor leads to the determination of the six degree-of-freedom sensor position and attitude data with respect to a reference frame fixed on the drogue.

The design and simulation of a controller for the docking procedure was also presented by Valasek et al [32]. Here, the drogue was assumed to be stationary. Tanker turbulence was treated as uncertain disturbance and was rejected by the control system. In the study, an Optimal Nonzero Set Point Controller is used in the flight control system of the receiver aircraft. The optimal controller developed by Valasek et al assumes that there are no exogenous inputs to the system. To improve the disturbance rejection properties of the controller to exogenous inputs, a low pass filter is used to pre-filter the control commands. Valasek et al simulated the system for the case of docking with a stationary drogue from an initial offset in three axes, with turbulence. They found that the system was able to effectively accomplish the docking task.

In the above control system design by Valasek et al [32], it was assumed that all the components of the state vector $\mathbf{x}$ are known. This may not be true in the real world. To estimate the state variables that are not provided by the optical sensor and also to filter out the process noises (gusts, tanker turbulence) and measurement noise for the sensors, Kimmett et al [21] improved the control system design by adding a variational Kalman Filter into the system. The controllers developed by Valasek et al [32] and Kimmett et al [21] are most suitable for tracking a relatively stationary drogue. Tandale et al [30] developed a Reference Observer Based Tracking Controller that does not require a model of the drogue or presumed knowledge of its position. A trajectory generation module is used to translate the relative drogue position measured by the sensor into a smooth reference trajectory, and an output injection observer is used to estimate the states to be tracked by the receiver aircraft.

Assume that the earth fixed inertial axis system (X_n, Y_n, Z_n) is oriented with the X_n axis pointing along the heading of both the tanker and receiver aircraft, and the Z_n axis points in the direction of gravity. The body axis (X_b, Y_b, Z_b)is attached to the receiver aircraft with the origin at its center of mass. Let (X_d, Y_d, Z_d) be the initial offset as measured along the inertial axis, between the mean position of the refueling drogue and the probe attached to the receiver aircraft. The drogue exhibits random oscillatory behavior in the plane parallel to the (Y_n, Z_n) plane and its mean position may be estimated by taking an average of the drogue position over a period of ten seconds prior to initiating the docking maneuver.

The reference trajectory is designed in two stages. In the first stage, the refueling probe on the receiver aircraft tries to line up behind the mean position of the drogue so that the initial offset (Y_d, Z_d) becomes zero. A smooth 5^{th}order polynomial trajectory is used to design the flight trajectory for the first stage. The parameters of this smooth spline are selected by imposing continuity, zero velocity, and zero acceleration at the initial and final times of the first stage. During the second stage, the probe follows the drogue positions along the Y_n and Z_n axis exactly. The reference trajectory is designed as a smooth reference trajectory between the mean drogue position and the current drogue position along the Y_n and Z_n axis. The reference trajectory which zeros the offset X_d is designed as a smooth 5^{th}order polynomial, but the initial and final times are the initial time of the first stage, and the final time of the second stage respectively.

To ensure that the reference trajectory is feasible and does not demand excessive rates in the states as well as the control, the time duration of the first and second stages are design parameters which must be judiciously selected as functions of the initial offset (X_d, Y_d, Z_d). The reference trajectory generated above is expressed in terms of the outputs δX, δY, and δZ respectively. The state feedback controller to be designed requires the knowledge of the full state vector for the reference trajectory. The purpose of the observer is to generate the reference states that the receiver aircraft should follow so that it can track the reference trajectory. The tracking performance of the Non-Zero Set Point Controller[32] was compared to the Reference Observer Based Tracking Controller (ROTC) [30]. ROTC shows less lag in the tracking performance and a 75% decrease in the tracking error.

Fravolini et al [19] proposed a fuzzy fusion strategy to combine information from GPS and machine vision system to determine the position of the drogue. They took d_G to be the distance between the receiver and the tanker as measured by GPS, and d_D the distance between the probe and drogue, as determined by a vision system. For large values of the distance between the tanker and receiver, the distance feedback measurement r_d

is provided by the GPS-based distance d_G. At intermediate distance, r_d is provided by a weighted combination of the GPS-based and the vision-based distance of the drogue. At small distance, r_d is the magnitude of the relative position vector of the drogue estimated by the machine vision system. When the refueling control system is activated at time t_0, the output of the fuzzy fusion system will be a large relative distance error $r_d\left(t_0\right) \neq 0$. To smooth the error signal to avoid actuator saturation or large accelerations especially in the first phase after the activation of the docking control system, an error weighing filter is used in the design. The authors showed with simulation that the proposed scheme satisfies the requirements for autonomous UAV in-flight refueling.

Campa et al [14] used the same fuzzy fusion strategy as that suggested by Fravolini et al [19] in their design of autonomous aerial refueling system with Boom and Receptacle method. In order to determine the relative position of the tanker aircraft with respect to UAV with machine vision system, markers were put on the tanker. In the study, the UAV dynamics is described by a linearized model. A reference trajectory is created when the AAR "tracking & docking" is activated at time t_0. The trajectory is expressed as a 3^{rd}order polynomial with respect to time t. The coefficients of the polynomial are evaluated by imposing desired boundary conditions. To ensure zero steady state tracking error for the position errors, the original linearized state space model is augmented with the integrals of the position errors. The design of the UAV docking control laws was formulated using a Linear Quadratic Regulator (LQR) approach.

For the autonomous aerial refueling system to work properly, an explicit knowledge of the position for all the markers is required by the machine vision system in order to find out the accurate relative position of the tanker. However, a small discrepancy of the real marker position with respect to the nominal design position might be possible due to effects such as tanker frame deformation. The effect of such discrepancy on the tanker position estimation error was simulated. The performance substantially deteriorates when the error on the exact location of all the markers is higher than 1%. The effects of the loss of visibility of one or more markers by the machine vision system were also studied. With a large enough initial set of optical markers properly located on the tanker aircraft, the estimation error does not seem to be substantially affected by the temporary loss of visibility.

Other control laws have also been proposed for the automatic flight control system for aerial refueling. Stepanyan, Lavrestky, and Hovakimyan [28] designed a control system for a receiver approaching and connecting up to the drogue with game theory, under the assumption that the position of the drogue can be measured by some method. Ochi and Kominami [25] observed that there are similarities between aerial refueling and missile guidance, where the proportional navigation guidance (PNG) is commonly used, and also approach guidance for instrument landing system, where line-of-sight (LOS) angle is precisely controlled. The observation led to flight control system design for automatic aerial refueling based on the PNG and the LOS angle control. In the PNG-based method, the longitudinal flight control system (FCS) controls upward acceleration and airspeed using the elevator and engine thrust, and the lateral-directional one controls side-ward acceleration and side-slip angle using aileron and rudder. In the LOS-angle-based method, the FCS controls integrals of flight path angle and flight directional angle along with the airspeed and side-slip angle. Simulation results show that both methods have good control performance under the circumstances without air turbulence. However, these methods may fail in the presence of turbulence.

It is believed that two of the most significant factors that affect the receiver aircraft's dynamics in aerial refueling are the time-varying inertia properties and the wind effect due to the tanker aircraft wake turbulence [15]. In the FCS designs mentioned above, the variation in receiver aircraft's mass is not considered. Pachter, Houpis, and Trosen [26] considered the variation of inertia properties in their design of an air-to-air automatic refueling flight control system. They considered mass variation using a quasi static method. The receiver aircraft is represented by sixteen models with different weights ranging from empty/low fuel to loaded/full fuel. A control system which is good for all sixteen models was designed. In this method, the dynamic effects of the inertia property variation were not considered.

Tanker aircraft wake turbulence is usually treated as disturbance in the controller design of FCS [32, 30, 26, 28, 25, 15, 14, 19, 21]. Dogan and Sato [15] designed a linear position-tracking controller with a combination of integral control and optimal LQR design similar to that of Campa et al. The controller does not use the information of the tanker aircraft's vortex induced wind effects acting on the receiver aircraft. To verify the performance of the controller, a set of nonlinear rigid body equations of motion for the receiver aircraft were derived. The nonlinear equations contain the wind effect terms and their time derivatives to represent the aerodynamic coupling between the two aircraft. These wind terms are obtained using an averaging technique [16].

7 Experimental Tests

Unmanned Air Vehicle has become an important asset in military operations. UAVs are invaluable in reconnaissance, target identification, target attack, and battle damage assessment. Autonomous aerial refueling extends the effectiveness of UAVs in several important ways. Challenges in UAV autonomous aerial refueling include [23]:

- Determination of the accurate relative position with tankers. The refueling procedure will require the UAV to operate in close proximity of the tanker aircraft. Therefore, it is critical for the UAV to know its accurate position with respect to the tanker aircraft.
- Collision avoidance. It is critical for the UAV to avoid collision with the tanker aircraft during aerial refueling procedure.
- Command and control. It is important for the UAV to respond to the boom operator's breakaway commands in the event an unsafe refueling condition occurs.
- Aircraft integration. Due to considerations relevant to cost, maintenance, availability, and constraints on weight and size, it is important to minimize the modifications to the tanker fleet and UAVs.
- Real-world constraints. AAR must be functional in all weather and day/night.

Flight tests and Man-in-the-loop simulation stations have been used to study the potential problems in UAV autonomous aerial refueling. One such man-in-the-loop system was developed by Burns et al [13].

As a part of the man-in-the-loop system, a prototype UAV control station interface for automated aerial refueling was developed by Williams et al [35]. It is used to control multiple unmanned air vehicles during the air refueling phase of flight. On the interface, the status of the tanker and UAVs are displayed. The operator creates high-level commands to move UAVs among different positions (observation, pre-contact, contact, post refueling) by mouse clicking. The high-level commands are sent to the UAVs. Having received high-level commands from the UAV operator, UAVs will generate corresponding lower-level trajectory commands for the UAV guidance, navigation and control systems to achieve the operator command objective. The prototype UAV control station interface is evaluated in a simulation environment with a KC-135 tanker and up to four UAVs simulated by computers. The interface performed satisfactorily though several issues are still to be resolved. In addition to the simulations on the man-in-the-loop system, flight testing has been used to verify the concept and possibility of automated aerial refueling of UAVs [24].

8 Conclusion

Demand for UAV autonomous aerial refueling capability has stimulated research activities in the area of aerial refueling. Aerial refueling research can be divided into four general areas: 1) Influence of tanker aircraft wake turbulence on the receiver aircraft; 2) the dynamics of the drogue and hose; 3) automatic flight control system design for aerial refueling; 4) experiments and flight tests related to the practical implementation of autonomous aerial refueling system.

Research work indicates that the tanker aircraft wake turbulence affects the stability and control of the receiver aircraft. The resulting forces and moments on the receiver aircraft can be predicted by either simplified models or by complicated CFD models. Researchers have studied the dynamics of the hose and drogue with FEA methods and experimental methods. Although progress has been made, it is still a challenge to accurately predict the position of the hose and drogue under the influence of the vortex field of the tanker wake turbulence and receiver aircraft nose. Such a prediction is actually impossible if random wind gust is assumed. Several automatic flight control systems with different control laws and position sensing methods have been proposed by researchers. Although most of the proposed flight control systems have been verified by simulations to satisfy design specifications, none of them has been verified by actual aerial refueling yet. UAV autonomous aerial refueling is still at such an early stage of implementation that there is no UAV available that is mature enough for modeling or actual flight experiments of aerial refueling. Other aircrafts (or models) are still used as “surrogate” UAV in simulations and flight tests.

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