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ABSTRACT

Unmanned Aerial Vehicles (UAV) are being required to be used in more and more complex situations with larger payloads for extended periods of time. Increasing the expectations and operating ceiling requires increased amounts fuel, that thus limits the potential payloads. This dichotomy has led to the quest for more fuel efficient UAVs; however, when designs are improved then their expectations are increased further. In manned aircraft this can be achieved by in-flight re-fuelling. This research is focused on the process of re-fuelling a UAV at low speeds and the aerodynamics considerations and problems it potentially brings. Practical conclusions to these concerns are addressed and recommendations for future research are identified.

Keywords: UAV, aerodynamics, re-fuelling.

INTRODUCTION

In-flight re-fuelling has been used since the early days of flight, the first recorded in-flight re-fueling was in 1923. The rather crude method of a simple hose and nozzle that was passed to the receiver aircraft has evolved into complex systems that deliver fuel at fast transfer rates. Figure 1 below shows how early trials and systems were very precarious. The likelihood of combustion and safe transfer was never consistent to be accepted as a practical solution for extended flight. Not until aviation became critical, World War II, did further attempts produce feasible solutions.

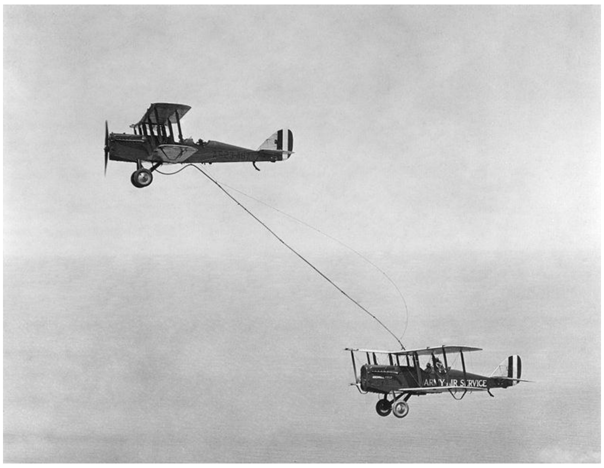

Figure 1, early in-flight re-fuelling.

These in-flight re-fueling systems have evolved into two principal types: boom and drogue. Below in figure 2 the Boom system is shown and the drogue in figure 3. For Boom systems the aircraft parks behind the re-fueler and a Boom arm is positioned by an operator on the re-fueler to dock into the fuel valve and deliver the fuel directly to the receiver. This system allows for a rapid transfer of fuel and more aircraft can be supplied in a limited time. Any aerodynamic movement from straight and level flight by both aircraft is accommodated in the Boom arm by telescopic extensions and gimbal joints. The Boom has winglets attached to increase stability whilst docking. The system in figure 3 is known as the drogue system. Here, a docking funnel is extended from the supplier aircraft and the receiver will fly to link its nozzle to the drogue, Bertin & Cummings, (2008). No intermediate operator is required and the receiver pilot docks directly. Any slack from aerodynamic movement in straight and level flight is accommodated by the extension hose. This system is not a capable for fast transfer of fuel as the Boom system, but is less complex. However, it is possible to re-fuel two aircraft at once as these drogue systems are mounted under each wing.

Boom and Drogue systems have their own operational problems and share common ones. For example, Dutch Role is where flight instability will result in a harmonic swing of the trailing aircraft. These are accommodated in the design and discussed above. The natural limitations prevent re-fueling when flight conditions are beyond agreed limitations and re-fueling is therefore not possible, Dole & Lewis (2000). Modern aircraft that are re-fueled in-flight have stall speeds in excess of 180KTS. UAVs have upper speeds of 130KTS and cannot receive fuel from existing re-fuelers. If UAVs are to be re-fueled in-flight then the function must be undertaken at low speeds and these have implications for the aerodynamic flight characteristics. Here it is proposed to re-fuel with a dedicated UAV re-fueler that will have the same flight characteristics.


Figure 2, Boom re-fueling systems.

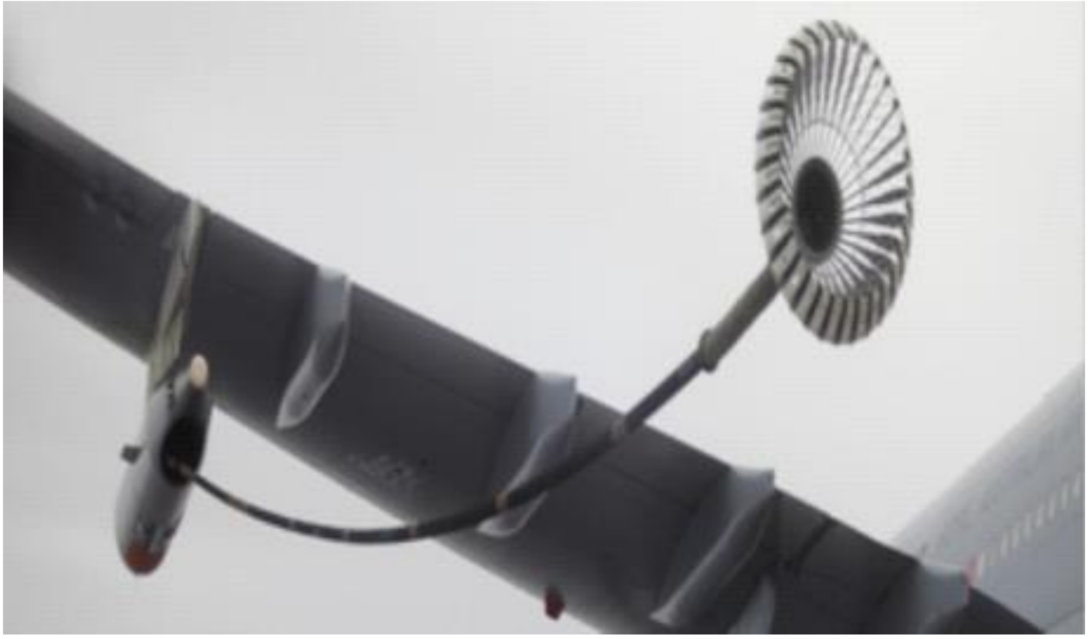

Figure 3, an underwing drogue deployed for docking.

In figure 4 you can see an aircraft that has docked with the drogue. Here the extension and position below the wash of the aircraft can clearly be seen. This positioning is critical, and assumptions are needed to determine appropriate positions, see methodology. The process of re-fueling a helicopter is on the very low limit of possible speeds by most re-fuelers. On occasions the re-fueling is done in a slow dive so the re-fueler will not stall and the receiver match speeds needed.

Figure 4, deployed drogue and receiver.

LITERATURE REVIEW

This section is a brief exegesis of the three principal areas of associated theory: aerodynamics of low speed flight, Crew Resource Management and automation & sensors usable for controlled flight.

The aerodynamics of low speed flight is defined and can be modeled to assess any requirement. Flight stability, or more accurately, flight in-stability is fundamental in these cases, Anderson (2005). Modeling low speed flight is now not limited to Wind tunnels and Computational Fluid Dynamics (CFD) offers advantages where minor modifications and improvements can be made to fine tune the model for further improvements REF. Wind tunnels can be used to validate CFD models and ensure confidence in the conclusions. Low speed flight is compounded by wind direction as it contributes significantly to the overall effective ground speed, Moir & Seabridge (2012).

At commercial aircraft cruising speeds any head wind will be small in absolute terms, likewise tail wind REF. At low speeds a head wind of 20/30 KTS could account for one-fifth of the overall ground speed. Head or tail winds will also significantly influence Dutch Role, McAndrew & Moran (2013). Such limitations are placed on flight patterns for re-fueling and can be accommodated for a given weather pattern. When weather changes suddenly this adds complications that again will change operational ability, McAndrew & Witcher (2013).

Crew Resource Management (CRM) is nowadays a basic need of Human Factors addressing the relationship, practices and management of those directly and indirectly involved in flight. Interfacing between the pilots, air traffic controllers, etc, is fundamental for a safe and error free environment. With UAVs the pilots are remote to the aircraft and this adds a further complexity to any system, Salas & Maurino, (2010). Remote docking by any system will require added technology to assist in extreme operating conditions, for example, poor visibility Ref. If there are concerns and collisions then with remote operation there is no danger to life. Generally re-fueling will occur above safe regions and terrain, Ferguson & Nelson (2013). If such systems are deployed in a war zone then risks to personal on the ground can be assessed. Nevertheless, errors or mishaps can result in crashes and total losses in equipment, Kanki, et. al (2010). UAVs are remotely controlled from far away and numerous examples of success can be found. When operated on 24 hours or longer the operators (pilots) can be changed as appropriate and in theory only ever need to land for fuel or maintenance. As this research addresses re-fueling pilot fatigue can be assumed to be zero; however, pilot skill can for docking must be high.

Automation is possible nowadays given the extensive range of sensors and integration systems, Berni et al., (2009). Autopilot systems are common place on most commercial aircraft and these are so advanced they can land in poor visibility. There are systems used Tracking, Collision, Avoidance Systems (TCAS) that are mandatory for commercial aircraft. Additionally, RADAR, ATC and GPS to ensure collisions are not possible. What these do not achieve are close flight characteristics as in close formation flying seen in display flying or in-flight re-fueling, Hruska (2012).

Linking two aircraft is both possible and feasible given available technology. There are practical concerns if Boom systems are the primary method as this adds an extra layer of complexity. For this research the Boom system is not being expanded and the focus will be on the drogue system. This is due to the Boom system requiring additional operations to dock with the receiver. Thus, both aircraft will need controlling and the Boom additional remote operation. A drogue system requires only both aircraft to be operated remotely. The re-fueler will need to fly straight and level during the transfer of fuel to give a target that is fixed within reason, whilst the receiver will fly to dock with the drogue, McAndrew and Witcher (2013).

RESEARCH METHODOLOGY

This work is based on the results from initial wind tunnel modelling of a re-fueler and receiver flying at low speeds and docking with a drogue. The height difference of each was set at 10 m, although this is not accepted as an optimum position and is part of a wider research project. The distance between them is set at 1.5 the length of the receiver.

Aircraft speeds of 90 and 140 KTS with head winds and tail winds of 10 KTS were used in this experiment. These are considered extremities of fuel transfer and the limits of feasible fuel transfer. Unlike commercial aircraft, these can change their heading accordingly to match weather conditions. The measured data to be collected are the lateral movement of the drogue in the X and Y axis, as this is the target of the receiver to dock. Once the receiver is docked any in-flight movement will be accommodated by the flex of the hose attached to the drogue.

Aerodynamically the drogue is designed to have vertical and horizontal stability. In this experiment the drogue is modelled as circular and follows the conventional designs in use. It could be possible to change this; however, the focus here is to review the operational envelope at low speeds.

RESULTS

In this experiment the extremes of the operational envelope were measured for the X and Y axis. These were carried out at 90 and 140 KTS and the addition and subtraction of 10 KTS head wind and tail wind, thus effectively, 80, 100, 130 and 150 KTS giving the appropriate ground speed. The result in summary are presented below in table 1.

	90 KTS		**140 KTS**	
	w/head wind	w/tail wind	w/head wind	w/tail wind
X-axis	410	500	230	320
Y-axis	250	350	170	240

Table 1, drogue deflection positions in mm.

In figure 5, below, the data is shown for the deflections in the X and Y axis for a drogue at low speeds of 90 and 140 KTS. The deflections follow an elliptical pattern with the lateral deflections being the greatest. These two graphs are representing a head wind of 10 KTS for each. In comparison the outer ellipse shows the positional changes that are experienced at the lower speed of 90KTS and the inner one represents the speed of 140 KTS. As the speed increases the deflections reduce, in effect, the target the receiver aims to dock is smaller and easier to dock. Inversely, as the speed reduces the target area for docking will increase and the likelihood for missing will be higher.

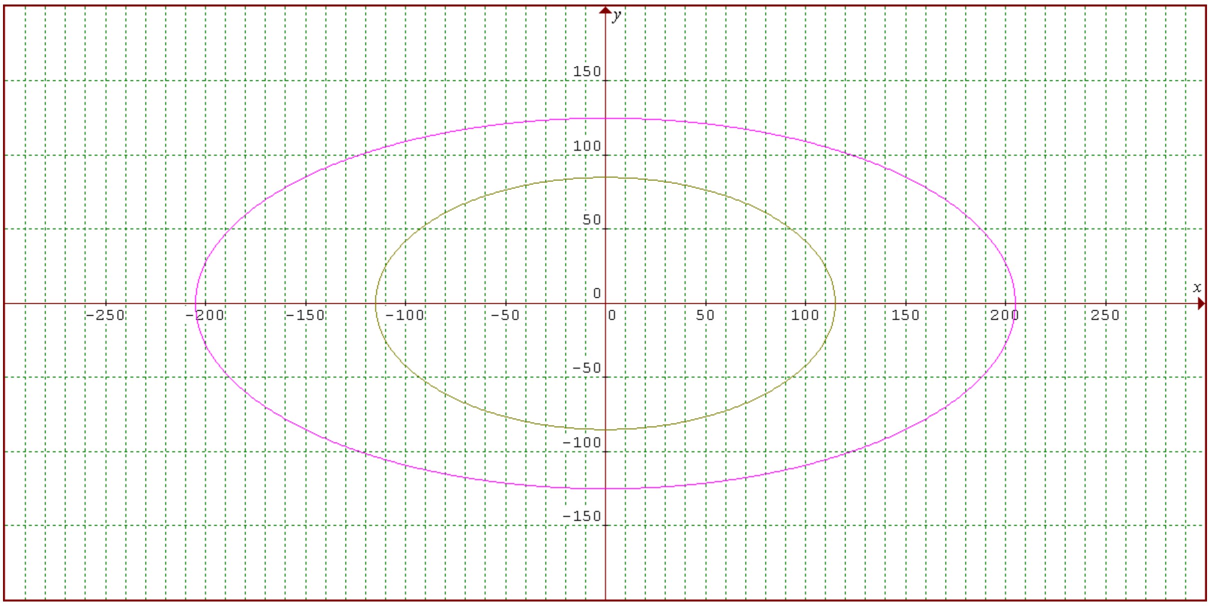

Figure 5, Comparison Chart for Drogue Deflection, 10KTS head wind for the flight speeds of 90KTS (outer ellipse) and 140KTS (inner ellipse).

Figure 6, below is the representation of the data at 90 and 140 KTS that have a 10 KTS tail wind. Again, the deflections can be seen and represent the target that the receiver will aim for the docking process. These data show a larger spread as the speed reduces and also the overall deflections are great than those with a head wind. The difference between figures 5 & 6 can be seen diagrammatically as they have the same scales that makes for visual comparison easier.

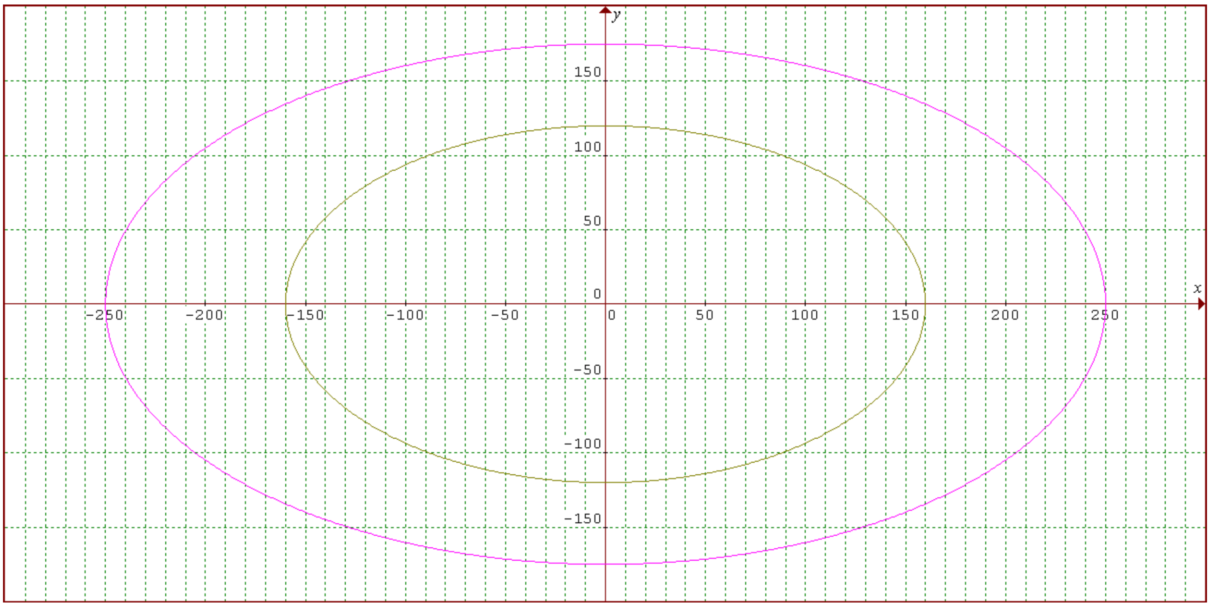

Figure 6, Comparison Chart for Drogue Deflection, 10KTS tail wind for the flight speeds of 90KTS (outer ellipse) and 140KTS (inner ellipse).

DISCUSSION OF DEFLECTION RESULTS

The results from this wind tunnel experiment show findings that cover three principal areas: pattern of deflection, influence of speed and compound influence of head wind and tail wind. Each of these is addressed separately below and the overall implications after.

Elliptical deflections show a variation in stability of pitch and role, perhaps even the inclusion of yaw in the total effect. It can be explained that the natural tendency of an aircraft is to Dutch Role and this produces the greatest influence in the X axis of movement. Observations, but not accurately recorded due to measurement limitations, suggest the movement will be harmonic in this deflection pattern and that is most significantly the reason why the Y axis has a smaller deflection in comparison to the X axis.

Speed of the drogue showed that as the speed increased the total deflection decreases *pro rata*, which can be explained aerodynamically. A drogue has high parasitic drag and is circular that will create vortices at the trailing edge and if these are relatively equal then the drag will become the predominant force inflecting deflection. What cannot be ascertained from these results is if the position of the drogue is nearer for farther away from the re-fueler if the turbulences of the wave will compound to increase deflections. This will be a follow on research question and not addressed in this paper.

Head winds and tails winds naturally influence aerodynamic forces on the drogue. What has been demonstrated here is that these two effects inversely influence the target position for docking. A head wind will reduce the deflections and a tail wind the opposite. This can be partly explained by the changes in parasitic drag as discussed above. This also clearly shows that at low speed re-refueling should be into a head wind or that it should not be with a tail wind. Clearly, a deeper understanding of these vales and within the range of 90 to 140 KTS needs more detailed measurement.

The total influence can be related to the drag from the drogue, speed and if a head or tail wind present. Operationally, the higher the speed the smaller the target for docking, and thus easier to achieve remotely by the pilots. The problem is that UAVs are operationally with limiting upper speeds and excess of 140 KTS is unlikely with current and developing UAV power plants. Weather conditions cannot be guaranteed, however, if there is a tail wind then flying in the opposite direction will produce a head wind. UAVs will be capable of being re-fueled in several minutes and thus not considerable delays achieved.

CONCLUSIONS

This introductory research into refueling has shown several seminal findings. First, drogue systems are going to be less complex, cheaper and requiring fewer personal to operate. Secondly, the deflections are elliptical in nature, possibly due to the influence of Dutch Role in flight. Thus a harmonic movement in flight will have implications for docking. Thirdly, speed reduces the deflections and the addition of a head wind aids this reduction. Inversely, a tail wind compounds the deflections and should be avoided where possible.

Finally, this research raises further questions to be answered. What distance behind and below the aircraft should the drogue be placed and can additional aerodynamic features to the drogue reduce the effect of Dutch Role on the deflections. If these are possible then the docking process can be simplified accordingly.

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