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Advances in air to air refuelling

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ABSTRACT

An increasing interest over the last decade in developing unmanned aerial systems' technologies has prompted research into methods for automating air to air refuelling processes. Furthermore, for systems with increased autonomy the necessary logic and flight control systems to perform autonomous air to air refuelling is now being pursued. There has already been significant research in position tracking, rendezvous scheduling, apparatus modelling, wake effects, and vision-based sensors to support refuelling of unmanned systems and to increase the autonomy in manned aircraft refuelling. Many of these build upon considerable research and understanding that has matured for manned air to air refuelling. This paper reviews the current, and future, state of research in this area.

Contents

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1. Introduction

Air to air refuelling (AAR) is an effective method of increasing the endurance and range of aircraft by refuelling them in flight. Its inception was in 1917 by the Russian–American Alexander de Seversky, and then followed by experimental demonstrations in the form of a fifteen-metre long rubber hose and manual flow valve in the 1920s. Since then it has been successively investigated, developed, and employed in endurance flights which led to the first non-stop circumnavigation flight in 1949. Plans to employ the method towards the close of World War II were not continued, and its first military use was consequently in the Korean War from the 1950s onwards.

Most recently there has been increasing interest in autonomous air-to-air refuelling (AAAR) for the continuing research into unmanned aerial systems (UAS). Over the last decade there has been a wealth of research and academic publications on the theoretical and practical aspects of automating the refuelling process covering aircraft control, sensor systems, and their integration. In order to develop and evaluate these simulation models ranging in fidelity from simple parameterised to complex physical representations for the aircraft, aerodynamic and atmospheric disturbances, and refuelling apparatus have been developed. This paper details the significant developments on these issues and highlights the current state of AAR and AAAR capability in the public domain.

1.1. *Refuelling methods*

The first AAR system that was robust enough for routine use was devised by the RAF squadron leader Richard L.R. Atcherly in the mid 1930s. The ‘looped hose’ system was a superior version of the original rubber hose method with additional connectors and fittings to streamline the hookup process. The patent for this was later purchased by Alan Cobham and further developed by his British Company Flight Refuelling Limited (FRL). It was utilised on small air freighters to save fuel costs by fuelling them in the air after takeoff [1]. This lasted very briefly however – it was abandoned with the onset of World War II. FRL received limited commercial interest after the war but was approached by the United States Air Force (USAF) who purchased a license for the technology in anticipation of what became the Cold War.

Both the USAF and FRL realised that whilst the looped hose method was satisfactory for cargo transports and large bombers, that carried sufficient crew to undertake the manual operations required, it was not useable on smaller fighter aircraft. Boeing was tasked with developing an alternative for the USAF, which led to the flying boom concept, first tested in 1948. Concurrently FRL succeeded the looped hose technique with the probe and drogue system, which debuted the year after. Both systems obviated the manual labour needed in the previous method, instead migrating the work to the boom controller, in the case of the flying boom, or to the receiver pilot in the case of the probe and drogue system. A third method, developed and tested in the Soviet Union in the 1950s, involved a flexible hose that was released from a Tu-16 bomber's wing tip that would be caught in a grapnel-like device trailed from the receiver's port wing, then winched into its refuelling port. This wing-to-wing method was only used on a small number of Soviet fighters and Tu-16 tankers due to its complexity, and replaced with the probe and drogue system in later aircraft.

Modern probe and drogue systems (Fig. 1a) are comparatively simpler and more compact than the flying boom (Fig. 1b) can be adapted to different aircraft and refuelling speeds, and their

a b

Fig. 1. Refuelling methods. (a) Hose and drogue. Photo by US Navy, (b) Flying boom. Photo by P.R. Thomas.

Table 1
Comparison of flying boom and probe and drogue refuelling systems.

Flying boom	Probe and drogue
Larger size, weight, and cost	Light and compact
Restricted to unary servicing	Multiple systems operable on one tanker, simultaneous servicing possible
Controllable via flaps	Passive, more susceptible to aerodynamic disturbances
Can use a boom-drogue adaptor to refuel probe-mounted receivers	Restricted to probe-mounted receivers
Not suitable for refuelling helicopters	Low speed drogues can be used to refuel helicopters
Workload is shared between receiver pilot and boom controller	Substantial pilot workload required to capture the drogue

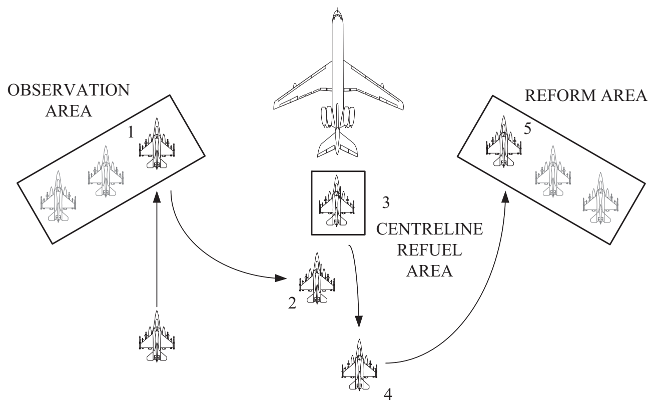

Fig. 2. Typical AAR refuelling procedure.

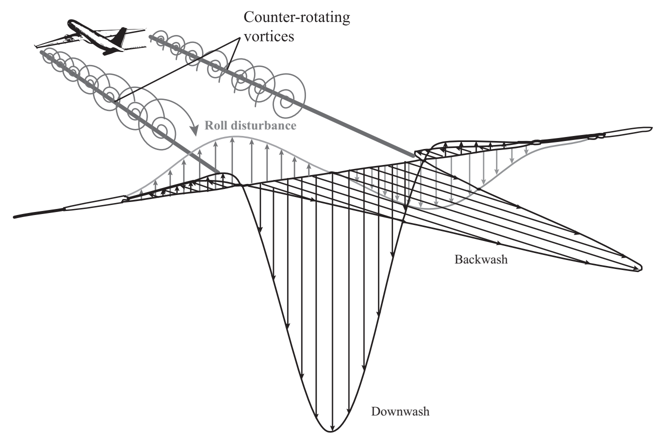

Fig. 3. Typical spanwise airflow disturbances from a trailing tanker wake.

arrangement on the tanker enables multiple aircraft to be refuelled simultaneously. The significant drawback is that additional, and somewhat substantial, pilot effort is required to control the speed and attitude of the receiver at such accuracy in order to connect with the drogue. The drogue is completely passive and subject to aerodynamic influence from both the tanker and receiver, which can make its capture a difficult task in turbulent and in night conditions. In contrast the flying boom is controllable via actuated flaps which the boom controller uses to direct the boom into the receiver's receptacle, whilst the pilot takes up formation at the correct position behind the tanker. Although the refuelling rates via the boom method can be much higher the size, weight, and complexity of the boom means that only one aircraft can be serviced at any time. Table 1 summarises the key differences between the two methods. These and other issues are highlighted in [2].

1.2. Autonomous air to air refuelling

A desire for long endurance unmanned aerial systems (UAS) is precipitating a need for automated refuelling systems, or autonomous air-to-air refuelling (AAAR). Nalepka and Hinchman [3] present an overview of the drivers and challenges associated with AAAR, the principal hurdles being:

- The ability to 'see near' in order to operate in close proximity.
- Collision avoidance.
- Command and control systems that must respond to human operator commands.
- Aircraft integration.
- Managing real-world constraints including weather, day and night conditions, and communication constraints.

A key desirable for an AAAR system is zero or minimal modification requirements to existing aircraft systems and airframes in order to reduce costs and extend the life of legacy systems. Similarly current operational procedures should be retained in order to satisfy equivalence requirements for airworthy certification. Interest in commercial solutions for long endurance surveillance and communication unmanned platforms will likely be the main driver for an AAAR capability in the civilian market; a market currently being explored in many countries.

1.3. Operational overview

The primary task required for the receiver across the AAR operation is relative position control. The receiver, after firstly rendezvousing with the tanker, is required to take up formation and manoeuvre around it. Whilst the exact nature of the manoeuvres can vary depending on the type and state of the aircraft and other external conditions, a standard operational procedure for an approach is mandated by NATO [4]; the approach for fixed wing aircraft is illustrated in Fig. 2.

The starting rendezvous location is the observation position where receivers enter a staggered queue. Following clearance granted by the tanker the receiver manoeuvres around the aft of the tanker to the designated refuelling line. For a probe and drogue system this may be either the centreline or from a wing-mounted pod. The receiver must approach the drogue in a stable manner and attempt to intercept it with the probe tip. The capture speed must typically be within 3–5 ft/s (approximately 1–1.5 m/s); the coupling will fail to latch below the minimum speed, whereas a violent reverberation through the hose (hose whip) can result in equipment damage at higher closing speeds. After a successful capture the pilot must push now the coupled probe–drogue assembly forward towards the tanker to open the flow valve, then maintain the receiver in a designated position behind the tanker during the refuelling process. This designated position is identified by a pilot via coloured marker bands on the hose, leaving between 40 and 70 ft (12–20 m) of trailing hose behind the refuelling pod. Once refuelled and cleared the receiver disengages, falls back, and manoeuvres starboard to the reform position before it is cleared to depart. With a flying boom assembly the receiver must stabilise at a position aft and below the tanker within reach of the boom, which is directed into the receiver's refuelling receptacle by the boom controller. The receiver must maintain its relative position until the boom is disconnected after which it can manoeuvre to the terminal formation position. To facilitate airworthiness certification it is likely that these procedures will be replicated in unmanned systems. Indeed, the oft requirement of such systems is that they can faithfully replicate the current capability of a human operator and will be interoperable with existing procedures.

2. Modelling

2.1. Aircraft models

Long range unmanned combat aerial vehicles (UCAVs) are likely to be the first beneficiaries of an AAAR system. The innovative control effector (ICE) is a tailless delta wing configuration typical of future UCAV designs that has been designed, and subsequently publicly released, for AAAR research purposes [5–7]. The low profile, all-wing, highly swept configuration affords the benefits of stealth, low wing loading, and increased aerodynamic efficiency. However it introduces control challenges in the form of reduced yaw authority due to the absence of a vertical tail fin, and reduced control power for downstream effectors that are subject to the downwash from deployed upstream flaps and spoilers. The Barron Associates nonlinear tailless aircraft model (BANTAM) proposed in [8] is based on data from wind tunnel tests from [9], with estimates from DATCOM and NASA's planar vortex lattice code HASC95, along with data on the effect of spoilers from the ICE model [6]. It features a leading edge sweep of 50° and is statically unstable at low angles of attack. Other UAV models have been generated from modified models of existing third and fourth generation manned aircraft such as the AV-8B Harrier (UCAV6), F-16, and F/A-18.

These aircraft models take the form of six degree of freedom, rigid body dynamics that are generally sufficient for solving the force and moment equations of aircraft throughout the entirety of the refuelling regime. Aeroelastic affects add increased complexity to any model, but would be of interest for the presence of particularly flexible structures such as high aspect ratio wings, or for detailed consideration of the effects of wake turbulence on external fuel or weapon stores. The aerodynamic data for these aircraft models are typically stored in lookup tables that in most existing models contain sufficient representation up to moderate angles of attack and sideslip. In the refuelling context however an extensive data set should rarely be needed as conventional refuelling via boom or drogue systems will occur at relatively benign attitudes and aerodynamic angles. Reducing the data set size where possible can then improve simulation run times. However as with any simulation exercise the range of data should be tailored to the scope of the research. For example, a larger data set would be needed for simulating moderate and severe turbulence where the direction of local wind, together with tanker downwash, can generate particularly high angles of attack.

A significant effect on the receiver's dynamics occurs with the uptake of fuel during the refuelling operation: there is a corresponding change in the receiver's mass, inertia, and centre of mass (CM). Whilst the reduction in mass from fuel burn introduces the same effects, the time period over which this occurs is notably longer than during the uptake of fuel. In both [10] and [11,12] the respective authors derived variable-mass equations of motion for the relative position of the receiver with respect to the tanker's position and attitude. The former work included atmospheric and wake effects in their equations, whilst the latter used a more detailed analysis of fuel entry position and velocity. It should be apparent that a distributed fuel system in an aircraft will cause changes in the CM as the fuel quantity changes. The corresponding shift in the static margin alters the trim conditions for flight and in a refuelling engagement, where the receiver is required to maintain relative position, requires appropriate adjustments to the control surfaces and throttle to compensate. Asymmetric distribution of fuel in the receiver has implications for roll control and may invalidate frequently made modelling assumptions on aircraft symmetry and negligible products of inertia.

2.2. Wake turbulence modelling

The vortices that trail from the tanker's lifting surfaces generate considerable turbulence for the receiver trying to stabilise behind it (Fig. 3). The receiver may also have to contend with engine jet wash, though this effect is considerably more transient. The effect on an aircraft travelling through a wake is akin to standard turbulence from the wind but with one significantly different property. Air turbulence from the wind is a stationary stochastic process with a zero mean, whilst the wake disturbances are nonuniform and temporally invariant for a given location in the wake and a given flight condition of the source aircraft. Some of the first work in producing a mathematical model of the wake was undertaken by Jewell and Stapleford [13] and Rossow et al. [14] in 1975 who utilised strip theory to approximate the turbulence effects. Later Kurylowich [15] used a pair of rotating vortices each with a viscous core and representative time decay effect.

Modelling and analysis of the effect of a tanker's wake on a receiver aircraft was arguably pioneered in several works by Bloy and his colleagues in Manchester University back in 1986 through to most recently in 2002. They first utilised a simple horseshoe vortex model to examine the effect on the lateral–directional [16], then longitudinal [17] stability of the receiver, reporting divergent oscillations in bank and sideslip, and degraded longitudinal stability from the influence of the wake. This degradation is primarily dependent on the vertical separation between the tanker and receiver [18]. From 1989 onwards they employed a vortex lattice method (VLM) to calculate the forces and moments generated on the receiver's wings. This offered results of fairly good agreement with wind tunnel measurements but often had discrepancies, accounted for by the simplistic horseshoe vortex model [19,20]. Later they used more realistic flat vortex sheets [21] and roll-up vortex models [22] to better represent the downwash distribution across the receiver's wing and capture more accurate induced rolling moment behaviour. A more detailed review of the research and findings by Bloy et al. can be read in [11,23].

Further work to that presented in [14] of a more experimental nature was conducted at the NASA Ames Research Center by Rossow and others [24–27], principally concerned with dealing with the hazards of wakes from transport aircraft. In [28] Rossow investigated the aerodynamic loads on a number of trailing wing sizes behind wings representative of subsonic transports configured for landing. Significantly, he noted that because of the assumption in VLM that the vortical flow filament is not affected by the trailing planform, the method can yield reliable results provided the trailing wing does not distort the flow significantly. This was found to be the case provided the ratio of the trailing to leader planform was less than 0.2. Increasingly above this limit he noted the trends in the predications still matched well but the magnitudes of the aerodynamic loads increasingly overshot. The research to this point is comprehensively documented in [29].

A series of research studies was also carried out by Blake et al. [30,31] to model wake vortex effects on formation flight of smaller fighter jets. In addition to investigating the effect on station keeping tasks they also looked at the induced pitching effects on the lead aircraft. One purposeful goal of their work was, through combined use of VLM (specifically, a modified version of HASC95 [32]) and wind tunnel data sets, to achieve sufficient understanding in order to reduce the size of the mathematical models without severely impairing their accuracy [33]. In [34,35] HASC95 was used, then compared with flight test results, to validate drag reduction estimates. Experimental measurements from flight tests were also looked at by Svoboda and Ryan [36] who derived models for the wake effects by comparing simulation and flight test data between isolated and refuelling scenarios. More recently Dogan et al. [37] reported on a similar flight test campaign where the wind data for the receiver and tanker were recorded for isolated and close proximity cases. By examining the data they were successful in separating out the wind effects due to prevailing wind, air, and wake-induced turbulence.

More recent investigations have been pursued for scenarios involving UAVs and autonomous air to air refuelling. Blake, Dickes, and Gringas [38,39] presented aerodynamic test results from a $30 \times 60\,\text{ft}^2$ wind tunnel with a 1/13 model of a Boeing KC-135R tanker and the ICE aircraft model. The tanker model was installed close to the top of the wind tunnel in order to minimise flow interferences from the mounting rig on the receiver. The tanker model included engine nacelles, refuelling boom, and an all moving horizontal tail. Four electric fans were mounted in the engine nacelles and run to simulate jet wash. Their results indicated that relative lateral and vertical position of the receiver induces a significant variation from the wake effects whereas the effects vary weakly with the relative longitudinal position [38]. Predictions of the wake field were made with the modified HASC95 code [32] and compared with the wind tunnel data. The dynamics of the forces and moments were predicted considerably well (approximately 25% peak error) except for the drag, most likely due to the absence of the effects of viscosity in the VLM code. They also postulated that neglecting the refuelling boom in the VLM model contributed to a notable discrepancy in the predicted lift at the refuelling position by a factor of two. In [40] experimental flight test data was collected for the downwash from a KC-135R on the USAFs surrogate Learjet by comparing pitch and angle of attack in close proximity flow. These were then compared to vortex lattice results which were found to be in error by as much as 50%. Comparison with CFD solutions offered a better match with the flight data (about 10%), and interestingly suggested that the flying boom was a significant source of the downwash effect.

Regardless of the particular technique used to model the wake turbulence and its effects, there are two main paths to implement the effects in a simulation environment: lookup tables or runtime code. The full vortex lattice methods are typically too computationally intensive for runtime simulations. Lookup tables containing the incremental changes in forces and moments are usually only valid for specific combinations of aircraft and require data sets of considerable size to avoid inaccuracy from interpolation. Furthermore, modifying the total forces and moments neglects the effects the wake turbulence has on the aerodynamic states of the vehicle. The airspeed, angle of attack, and sideslip are functions of the local air flow, the changes on which are not modelled when the turbulence effect is encapsulated only in force and moment increments [41]. Therefore for a full physical description of the aircraft the disturbances must be represented in aerodynamic form.

Departing from the methods they had previously used Bloy and Khan [42] aimed to reduce the computational overhead by resolving the wake effects to a single point at the centre of gravity of the receiver. By assuming linear distributions for the downwash and sidewash on the lifting surfaces the aerodynamic loads can be readily calculated which are then integrated across the lifting surface. Compared with the previous methods this ‘single-point model’, as it is sometimes referred to, had reasonable accuracy when the receiver-to-tanker wing span ratios was much less than unity. That makes this particular formulation poor for analysing large receiver aircraft but the computational efficiency makes it suitable for fast, real-time simulation. With the same goal Saban et al. [43,23] sought a computationally efficient method of modelling both upwash and downwash from a UAV to be used in multi-vehicle maneouvres. This leads them to use a hybrid method utilising Weissinger's extended lifting line theory to model the horseshoe vortices, along with Kurylowich's model for the vortex velocity distribution profile. These methods were chosen based on a compromise between simplicity, accuracy, and computational cost.

Venkataramanan and Dogan [44] took a different approach and devised a Vortex Effect Modelling Technique (VEMT) which was amenable to their reformulated equations of motion [10]. This was achieved by deriving an approximate uniform description of the wake turbulence and downwash gradients, made by averaging these quantities over the surface of the receiver's planform, which is again resolved to act at the centre of gravity. The wake disturbances were written as a function of the relative separation and relative orientation between the two aircraft. The data to base these functions on were obtained using a modified version of Helmholtz' horseshoe vortex model, with a correction term using Kurylowich's finite core radius to remove the singularity in Helmholtz's formulation. A scheme to fuse a single-point data set with pressure distribution data, and thus take into account local wind gradients across the wingspan has been attempted [45], though at the time was restricted to less-than-real time operation due to computational demands.

2.3. Downwash and upwash

In addition to the trailing air vortices the receiving aircraft must contend with downwash of airflow from the tanker. The affected local airflow typically exhibits a nose-down pitching moment on the receiver which, in turn, affects its speed and approach rate. Naturally, this effect increases with proximity to the tanker. Similarly, but mostly between large transport aircraft, the lead aircraft experiences a change in its airflow caused by the bow wave, or upwash, from the receiver. This increases the angle of attack around the tanker's tail which also results in a pitch-down motion. Under-running the tanker is particularly dangerous since the downwash effect will dissipate, resulting in the receiver pitching up. At the same time a tanker on altitude hold may instigate a nose-down pitch due to a perceived climb due to the decrease in pressure in the surrounding air [46], potentially leading to collision. These complex dynamic interactions are managed by slow approaches in order to introduce the effects to the pilots gradually. This also extends to a need to separate and depart gradually.

These pitching moment effects, although not extensively studied, have been demonstrated both analytically and experimentally. Vortex-lattice-based simulations as early as 1985 [47] indicated the reasonable accuracy of the technique, but the significance of the absence of the fuselage contribution, and other non-lift producing parts, to the downwash and upwash flows was demonstrated more recently [48]. Ryan and Platz [49] quantified the changes in the aerodynamic pitching and rolling moment coefficients between C-141 and KC-135 tankers. By identifying the off-trim pitch and rolling behaviour they were able to obtain moment perturbations caused by the aerodynamic interactions. Usefully for simulator design, this meant that the complex aerodynamic effects could be represented by multi-dimensional look-up tables.

The effect on the tanker is predominately a pitching moment since, even in an off-centre approach, the receiver upwash does not reach the tanker's wing. However the effect on the receiver is both a pitching down moment, and in the case of off-centered formation, a rolling moment from the asymmetric lift distribution across the wing due to both the wing tip vortices and the tanker downwash. Furthermore the effects discussed on the tanker are also only of sufficient magnitude when dealing with the interaction between larger, transport aircraft. However the upwash from smaller receiver aircraft may have an implication on the boom and paradrogue dynamics, but more-so on the latter.

2.4. Boom modelling

The flying boom is a gimballed, telescopic probe that through use of mounted control surfaces can be guided and inserted into the refuelling receptacle on the receiving aircraft. As this guidance is presently human operated they require the necessary training, and simulation naturally plays a key part in this. An empirical model of a flying boom was developed as part of the US Air Training Command's (now Air Training and Education Command) Boom Operator Part Task Trainer (BOPTT) facility, details of which can be found in [50]. This model has since been incorporated into the US Air Force Research Laboratory (ARFL) refuelling studies. The model featured a non-retractable rigid body with rotation about the boom root which translated through the air. Aerodynamic, gravitational, and control input terms were applied directly to equations which computed the moments about the boom root joint. This model was later updated for research into improving operational capability by adding variable mass and inertia to represent the effect of the retractable boom, physical geometry, aerofoil data, and component weights [51]. Aerodynamic and gravitational forces were then evaluated via component build-up.

Whilst the BOPTT model and its derivative were considered satisfactory for training and general research purposes they both lack dynamic coupling effects between the tanker and the boom. One such effect is the subtle change in tanker trim due to boom motion and orientation. Significant boom motion can even cause the tanker to roll into a turn, effectively making the boom a pseudo-rudder [46]. Where precision modelling and simulation are required, such as for AAAR, these effects were seen as important. Consequently Smith and Kunz [52] set about deriving a new set of multi-body system equations and aerodynamic terms to characterise the fixed and extendable parts of the boom, before coupling them with the tanker model.

Both Doebbler et al. [53,54] and McFarlane et al. [55] employed the data from [52] to develop simplified dynamic models without the coupling effects on the tanker motion. On the other hand Fravolini, Vendra et al. [56,57] favoured a 3D finite element method (FEM), an approach typically used to model robot manipulator dynamics.

2.5. Hose and drogue modelling

Unlike the flying boom, the hose and drogue system is inherently more complex to model since it consists of three parts with disparate dynamics: the drogue, the hose, and the hose drum unit (HDU). The infinite degrees of freedom and nonlinearities inherent in a flexible bending structure make modelling the hose particularly challenging.

A common approach to modelling the hose is to reduce its total length into a series of connected elemental linkages. Zhu and Meguid [58] note that a hose or cable, and an element of such, is typically idealised as a slender body due to its large ratio of length to diameter. However situations of low cable tension, which occurs in refuelling hoses, can result in large or violent oscillations (e.g. hose whip) that classic cable theory cannot accurately deal with. Its limitations at low tension are attributed to the occurrence of a singularity when the tension disappears anywhere along the cable, and the omission of bending stiffness. Alleviating the singularity problem can be achieved through the addition of artificial damping, higher order terms and bending stiffness [58]. Unfortunately such a realistic and high-fidelity cable model inevitably results in a complex set of partial differential equations which must usually be solved through iterative numerical methods. Eichler [59] attempted this task back in 1978 with a set of linear hyperbolic partial differential equations, however his model was restricted to small perturbations about the hose's natural catenary.

Fravolini et al. [60,61] developed a finite element method (FEM) model, which was used later to formulate their flying boom models [56,57]. Lagrangian mechanics provides the solution for the position of the linkages and their formulation included the effects of wind forces. However only three straight linkages for their hose model was used with the first being rigidly attached to the tanker. The main difficulties with using FEM for low-tension cable problems are:

- the lack of a simple beam element that can handle curvature together with large displacements and rotations and
- mathematical formulation of generalised flexible beam elements is more complex than for finite difference methods.

Straight beam elements violate continuity conditions for the slope and curvature of a slacking cable since the effective discretisation of the cable results in excessive bending stiffness or membrane locking occurring [62]. Curved elements, on the other hand, yield higher accuracy using coarser meshes but their formulation is not a simple extension of straight beams. These limitations motivated Zhu and Meguid to propose an alternative element, inspired by the concept of coupled consistency displacement fields, and extended its use to the modelling of an aerial refuelling hose [63,64]. This formulation was verified against experimental data from the free-swinging of a steel cable before being used to model a hose and drogue system, showing expected phenomena such as oscillation due to disturbance at the tow point, and hose-whip due to failure of the reel mechanism to take in slack during the coupling process.

Bloy and Khan [65], a series of studies by Vassberg et al. [66–68], and later Ro and Kamman [69,70] all applied a simpler lumped parameter approach based on multi-body dynamics. The hose is approximated by straight, elemental linkages which are subject to aerodynamic, gravitational, and internal tension and torsional forces at both of their ends. Equilibrium equations can be written for each hose element, and subsequently propagated along the entirety of the elements. This permits a straightforward Newtonian solution for joint motion, with link tension derived from a constraint on the length of link elements. For the aerodynamic forces on the hose an inclined-cylinder drag method due to Hoerner [71] is commonly used.

The hose models developed at Boeing by Vassberg et al. were based on a model previously created in 1993 for modelling the hose whip phenomenon, but with the addition of aerodynamic forces due to the surrounding flow (calculated using a panel method) and the distributed loads due to pressure and skin friction drag. In [66,67] the drag on the drogue was taken as point force acting in the local flow direction before being improved upon in [68] to take into account the unsteady and non-uniform flowfield about the drogue during a coupling event by basing the drag on the flow environment around the basket rim. Further to the aerodynamics were an implementation of the restoring hose bending moments based on simple beam theory, and a representative model for the reel take-up system in the HDU modelled with a second order linear differential equation for a rotating mass with angular acceleration. Simulations of the hose tension in [66,67] and then later by Ribbens et al. [72] demonstrated the necessity for the tension control provided by the reel take-up system in order to suppress the hose whip behaviour. Post-contact simulations in [73] focused on the loads on the refuelling probe during a hose whip, showing that downward motion of the receiver into contact exacerbates hose whip by increasing the hose angle of attack, whilst upward motion into contact can be used to provide the opposite effect.

For their hose model Ro and Kamman added a parametric model of the drogue aerodynamics derived from wind tunnel experiments and CFD simulations [74]. In that study they investigated the drag characteristics of a paradrogue assembly as a function of its geometric parameters. CFD results were found to agree well with the wind tunnel results, except that the CFD simulations under predicted the drag coefficient. This was attributed to a simplified canopy profile image and the software misrepresenting the wake from the paradrogue and the flow separation. In [75] difficulty in sizing the mesh for the canopy (an order of magnitude less than the canopy fabric thickness) led to its exclusion from all 3D simulations, instead relying on simpler 2D flow solutions to provide qualitative results for the lift force on the canopy. CFD analysis of a high fidelity canopy model remains a challenge.

Despite Zhu and Meguid's criticism of straight-element models and the lack of inclusion of bending forces, Ro and Kamman argue for the numerical accuracy of their lumped parameter approach, stating that convergence studies demonstrate that a relatively low-fidelity 20 linkage model and a time step of 10 ms produce results that are close to higher-fidelity models. They verify their simulations against available data from flight test data (see the following paragraph), confirming reasonable agreement with both static and dynamic cases. The lack of inclusion of bending stiffness in the model might be seen as detrimental, but Ro and Kamman's validation against flight data suggests this to be an effective and computationally efficient method.

Experimental efforts to develop a flight-validated dynamic hose and drogue model occurred between 2004 and 2005, details of which were published by Hansen et al. [76–78] on the NASA Dryden Flight Research Centre (DFRC) 'Automated Aerial Refueling' project. This involved a series of flight tests using two NASA F/A-18 aircraft and a conventional hose and drogue system. A quadruplex, time-synchronised video system was used: two cameras at the rear of the tanker aircraft looking towards the receiver, and a further two at the front of the receiver pointed towards the tanker, in order to provide two stereoscopic measurements of the hose and drogue dynamics. Twelve research flights were flown under multiple flight conditions to obtain flight data. In order to aid development of accurate hose and drogue model, flight test manoeuvres exciting the dynamics of the hose and drogue system were also developed and executed. Results (of a mostly qualitative nature) are presented for the steady-state drogue position with airspeed showing that the drogue position climbs with increased tanker airspeed, following what appears to be a gentle curve. A similar though inverse relationship between drogue location and tanker angle of attack is also identified. An attempt was also made to characterise the bow wave effect by static mapping of the displacements of the drogue due to the receiver at various grid points, firstly by moving the receiver to each grid point, then via quasi-static, steady-rate sweeps through the grid points. Doing so allowed an 'area of influence' to be established at two flight conditions, which quantified the area in which the proximity of the receiver's nose had a notable influence on the drogue's position. Of note was that at about 8.6 kPa dynamic pressure the area approximates a circle centred on the drogue, whereas at the lower 6.2 kPa the area was more elliptical. Although the measurements were taken in static conditions they are still indicative given that the approach speeds for a successful capture are relatively low. For such approach speeds Bloy and Khan [65] equally note that the displacement due to the bow wave of the receiver (in this case a Panavia Tornado) can be approximated to a reasonable accuracy via a static analysis of the hose and drogue's motion. Likewise in [68] the flowfield around the drogue was modelled by superposition of a time-marching flowfield around the receiver onto the flowfield of the tanker. In order to compensate for the induced drogue motion a vertical-plane offset in the starting position for the probe's approach was used such that the drogue would deflect into the approaching probe. Naturally these offsets are highly dependent on both the starting range and the closing speed.

Other test data and analysis from NASA flights and published in [79] inferred drag measurements for a high-drag configuration drogue through variations in engine thrust as the paradrogue was deployed, at airspeeds between 170 and 250 KIAS. Analysis of the drag polars suggested an inverse linear relationship between the drag and airspeed, and only minor dependence on altitude. A constant drag coefficient of 0.0056 for the flight range examined was then extracted. The drag relief on the tanker whilst the receiver was engaged was also obtained from the data and ranged from 155 to 1200 N, corresponding to the airspeed limits mentioned previously, again in a linear manner. When this data was compared to extrapolated wind tunnel data, the trend in the flight test data matched that of the wind tunnel, although the flight measured values were up to 25% lower at the higher end of the airspeed range. Interestingly the error was on average lower towards 170 KIAS, but the spread in the error was greater. Both the spread and magnitude of these errors could be attributed to multiple variations in the experiments: air turbulence, stability of the paradrogue assembly position, shape of the paradrogue canopy (sometimes deformed after engagements), and the effect of changes in the airplane trim.

Lastly, it is worth noting that the dynamics of the hose will change during fuel flow. In [80] a refuelling process with trailing, fuel transfer, and rewind phases was modelled with the commercial CFD software Flowmaster in order to characterise the fuel-transient behaviour.

3. Sensors

3.1. Feasibility and requirements

An autonomous system for air to air refuelling must be capable of measurements primarily of a spatial nature for both tracking and station-keeping tasks. The closer the receiver approaches the tanker, the greater the requirements of a sensor system for either of these tasks will become. Current technologies that have been solutions for similar situations have been

1. Global navigation satellites.
2. Machine vision.
3. Radar.
4. Electro-optical (laser).

In [81] minimum sensor detection range and the sensor field of regard (FOR) were the primary drivers for the implementation of a totally autonomous UAV capable of rendezvousing with a tanker. In the hookup phase the resolution of these measurements will need to be in the order of metres and centimetres for the station-keeping and tracking tasks respectively. High bandwidth will be necessary to react sufficiently to the close proximity motion, and corresponding measurement and processing delays must be kept to a minimum.

It is also worth noting that operational requirements of AAAR may be driven not just by sensor technology but also from procedures used to rendezvous with the tanker [81]. Although these procedures should follow those adopted from manned aircraft as a starting point, they should not necessarily be restricted to them if improvements with autonomy allow for a better approach.

3.2. GPS

Modern Differential GPS (DGPS) systems can typically provide submetre positional accuracy with nanosecond time transfer accuracy, whilst commercial services such as that provided by GALILEO will provide greater accuracy with additional value-added data such as integrity data and wide area differential corrections [82]. However such satellite systems do not yet readily provide positional data at the frequency needed for high speed tracking, such as close proximity tracking of a paradrogue. There are also a myriad of issues with GPS in general which prohibit their exclusive use. These issues include satellite drop out, hostile jamming and spoofing, multipath effects, and dilution of precision. Installing a GPS receiver on a drogue also brings back the issues surrounding the provision of power to the drogue unit and would require additional flight clearance tests to ensure that it was sufficiently robust to survive refuelling engagements [76]. Concerns that the tanker might obscure the view of satellites and severely affect the positional accuracy of any GPS-based system may be unwarranted however. Khanafseh and Pervan [83] produced a detailed sky blockage model for use with a KC-135, validated through flight tests. Several grid points set across the earth's surface were used to evaluate world-wide GPS availability. A coarse blockage model suggested a drop in availability to 77.2%, however the worst case availability in a more accurate, higher-fidelity model was stated as 99.3036% with an average value of 99.9985%. Such higher percentages would suggest that GPS blockage is a mute issue. However a few discrepancies between their blockage model and flight test data were noted, and attributed to multipath reflection or diffraction due to the tanker. GPS signal availability could also be affected by moderate bank angle manoeuvres [84].

A combination of GPS and inertial measurement unit is commonly used to improve the position and tracking performance for an aircraft. With a high accuracy GPS system this offers a potential solution to sufficient tracking accuracy for engaging a drogue or refuelling receptacle. One important issue with using any GPS-based system to obtain relative position information is that, putting aside independent sources of error, in order to avoid inherently different measurements both bodies must track the same satellites. Research for the US Navy's Unmanned Combat Air System Demonstrator (UCAS-D) programme has looked at approaches for relative position satellite measurements. One solution is to transmit GPS measurements from the tanker to the receiver to obtain a carrier-phase based solution for the relative position. A relatively precise measurement can be gained by using algorithms that are currently employed for GPS-based aircraft carrier approach and landings. Inertial navigation data from both aircraft can be used to produce a relative inertial vector for real-time guidance which, after being calibrated with the high-precision GPS measurement, gives the displacement to the desired waypoint or refuelling position. This method however is still susceptible to degradation when satellites are lost or obstructed. Follow up development in [85] allows both tanker and receiver to perform precision navigation independently using precision ephemeris correction updates for the GPS signals. Using the ephemeris updates reduces GPS error further and assists in convergence of the GPS/INS solution, eliminating step changes that previously occurred during satellite switching. This P-RELNAV system also has the benefit of backup navigation using the Link-16 tactical data exchange in GPS-denied environments [86]. Civilian systems using commercial or freely available GNSS systems would require similar levels of security and integrity and access to backup networks to avoid the effects of interference, jamming, or signal spoofing. The nature of these systems also requires significant amounts of data to be transmitted between the tanker and receiver which is another point of failure that would need to be addressed.

3.3. Machine vision

Object identification in UAS operations by image-based inspection is an increasingly popular field of study. Research has been carried out in applying vision sensors to navigation [87,88], tracking [89], collision avoidance [90], automatic landing [91], and aerial refuelling [92,93]. By detecting and identifying key information of a target from a two-dimensional image from a camera, relative position and orientation can be inferred when the location of the camera is known within a global coordinate frame. The reliability of vision systems are however susceptible to environmental conditions such as cloud, fog, and lighting conditions, and have varying levels of computational processing requirements.

A commonly proposed means of identifying and tracking the drogue is by identifiable beacons mounted on the drogue's canopy. Junkins et al. [94] developed an optical position and orientation measurement system employing a lens and a position-sensing diode capable of detecting the line of sight of a light source, without digitising the image. By employing sequenced illumination of beacons in known locations on the target, in conjunction with a communication link between the sensor and the beacons, the system can triangulate the position and orientation of the target with update rates up to 100 Hz and relatively meagre processing requirements. This method is used in a number of AAAR studies by Texas A&M University for a ‘vision-based navigation system’ (VisNav) [95,96]. It requires at least four beacons to be mounted to the drogue, and communication with a beacon control unit to sequentially activate and deactivate each of the beacons. In [97] they suggest that extremely accurate and precise real-time navigation is possible utilising VisNav which is capable of providing six degree-of-freedom positional information to an aircraft's FCS. Also advocating the use of beacons, Pollini et al. [98,99] proposed placing light emitting diodes (LEDs) on a drogue and using an inexpensive CCD camera with an infra-red filter to identify the LEDs. Similarly placed on a lead aircraft, LEDs could be used for formation flight control.

There are a few notable disadvantages with the use of beacons in probe and drogue refuelling. Firstly, conventional refuelling hoses are currently not designed to carry electrical power, and provision for such power requires non-trivial modifications of the tanker equipment. The alternative would be to mount batteries inside or on the drogue, which would require modification and most likely redesign of the para-drogue assembly. This would need to be have guaranteed isolation from the fuel supply to avoid igniting the fuel. Secondly, for stealth reasons it may be desirable to operate with minimal external lighting. The above methods are examples of active systems because they require some form of cooperation (usually data communication) from the target to operate.

Passive systems do not require cooperation from the target and so will require less modification to equipment, but also are the only option when communication is limited or denied. Corner detection methods (and interest point methods in general) rely on prominent features in an image that have well-defined, meaningful positions that can be reliably detected. Corners (effectively the intersection of two edges) can be easily identified in images, though other interest points may also be detectable.

Two frequently used methods for corner detection in AAAR studies have been the Harris and SUSAN algorithms. Harris and Stephens' algorithm [100] addressed limitations in a method by Moravec [101] which worked by determining the average changes of image intensity that occurs from shifting a local patch of the image by a small amount in various directions. Their improved algorithm instead considers the differential of the corner score with respect to direction directly, instead of using shifted patches. Other improvements were then made by Noble [102]. In contrast the SUSAN (Smallest Univalue Segment Assimilating Nucleus) corner detector [103] operates based on a brightness comparison in a circular mask. The work by Fravolini, Vendra et al. [56,57] compared the Harris and SUSAN corner detection algorithms, reporting that in general the Harris algorithm provided better performance compared to the SUSAN algorithm in detecting the same corners in every frame while yielding a decrease in false positives. They also suggest that the Harris algorithm provides increased robustness at the expense of computational power. Spencer [104] made use of the Harris corner detection algorithm to extract both structural and painted features on a tanker. For each video frame the detected features were compared to known features on the tanker to compute the 3D pointing vectors. A Kalman filter-based navigation algorithm then provided the relative position of the tanker. Data from a flight test carried out by the USAF Test Pilot School using a C-12C and a Learjet LJ-24 was used to test the algorithm, where feature estimation was found to be the dominant source of error. They concluded that the performance of the algorithm was heavily dependent on the accuracy of the filtered-navigation updates.

More feature-intensive detection algorithms have also been attempted. Saghafi and Zadeh [105] had success with a pattern recognition approach, although it was reliant on a radial basis neural network and was slow to converge. Generally the large computational overhead associated with pattern recognition techniques can lead to comparatively low update rates and reliability is an issue in various lighting conditions. The work in [53,54] demonstrated a deformable contour algorithm (so-called 'visual snakes') which utilised weighted colour statistics to converge on the outline of docking margins around a refuelling port, and estimate the position of the receiver with a 30 Hz refresh rate. The visual snake can provide not only information about the target size and centroid location, but also information about its shape through the lengths of its principal axes.

After detecting the target, the problem of relating the points extracted from the camera image to the actual features on the tanker can be formalised in terms of matching the set of points of the image to the known location of points in the model. Mammarella et al. [106] evaluated two point-matching algorithms: Mutual Nearest Point (MNP) and Maximum Clique Detection (MCD), for use in a MV-based AAAR system. Both algorithms were found very similar in terms of accuracy however the MCD was generally able to recognise more corners and provide better matching when the projected points were closer to the detected points on the image, even more in case of real images. However as well as requiring less computational power, MNP was found to offer better consistent overall matching. The quality of the matching has a significant effect on the accuracy of the final pose estimation. In [99] a matching validation phase is integrated with the pose estimation stage so that, from a set of matched images with associated collinearity errors, unfeasible poses can be discarded leaving a final estimate from the match with the smallest associated error.

All of the above methods make use of features inherent to the aircraft, or additional equipment such as beacons and painted marks that require installation or modification of the drogue, tanker, or receiver. These *feature-based* methods first extract a sparse set of distinct features from each image separately

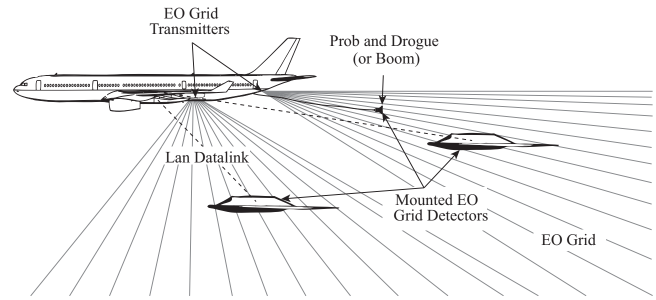

Fig. 4. Electro-optical grid reference system (EOGRS).

(detection), and then recover and analyse corresponding parts in order to determine the motion and location (image mapping). In contrast, *direct* methods recover the unknown parameters directly from measurable image quantities from all pixels in the image [107], thus have the potential to be more robust in the presence of visual occlusions. Most direct methods comprise two constraints involving brightness constancy and a motion model. Basic direct methods rely on linearising the displacement of brightness of pixels across two images, which is satisfactory when the motion of pixels is relatively small i.e. at large distances from the target. Hierarchical extensions allow the detection of larger image motion via coarse-to-fine refinement of the parameters in the motion models, which is critical in the context of turbulence effects that will produce sudden, large motions in the image plane. Hierarchical methods are also computationally efficient when lower resolution computations are carried out for the larger displacements, then using higher resolution information to improve the accuracy by incrementally estimating smaller displacements [108,109].

A final task of pose estimation involves determining the necessary transformation of the 2D image to give the target's three-dimensional relative position and orientation. The two most commonly used algorithms for this have been Gaussian Least Squares Differential Correction (GLSDC) and the Lu, Hager, and Mjolsness (LHM) algorithm. The GLSDC algorithm [110] is based on the Gauss–Newton method for the minimisation of a non-linear cost function, derived in terms of the difference between the estimated and detected positions. The algorithm offers the best geometric solution in the least squared sense [60], and was employed heavily in the VisNav system [96,111]. In [98,99] images from an IR camera were fed into the LHM algorithm [112] to determine the relative position and attitude of a drogue. Indoor tests and simulations with natural lighting conditions demonstrated that the algorithm was able to make reasonable estimates of the position of the target, even with some markers unidentified. In comparison to the GLSDC, the LHM has a similar level of accuracy however has a significantly higher level of robustness albeit at the expense of greater computational effort [113,114].

3.4. Radar

There is no widely available investigation into using Radar as a means for range detection in AAR. Systems akin to fire control Radar would seemingly be suitable. However ensuring the target of interest (the drogue, for example) is identified correctly may require either the installation of absorbing material, or additional processing of the image to separate the target from the tanker. Radar frequencies in the region of 75–110 GHz (2.7–4 mm wavelengths) have been used successfully as range finders for experimental autonomous ground vehicles [115], but will easily be absorbed by atmospheric moisture. Water vapour present in the air effectively restricts radar signals to below the K band (18–24 GHz) which are unlikely to be accurate enough for close range docking. Additionally, moisture and the temperature lapse rate can cause ducting where the electromagnetic energy is deflected as it passes through lapse boundaries, affecting the radar's horizon. Larger water droplets, ice formation, and dust particles in the air will all cause attenuation of the signal energy, and thus affect the signal range.

3.5. Electro-optical

Typical laser range-finding lidar systems, like radar, utilise reflection delays to compute the range and have an advantage over vision-based systems in that they are not susceptible to motion-blur or obscuration by fog and clouds, or ambient light [116,117]. They are however, like radar, susceptible to attenuation by clouds, ice, and dust, and possibly water vapour in the air depending on the laser wavelength. The attenuation of electromagnetic energy by water vapour is perhaps a significant drawback compared to vision-based systems, which are not limited by this inherent, and variable, atmospheric property.

In contrast to a lidar system, an electro-optical grid reference system (EOGRS) developed by GE Aviation [118] calculates receiver aircraft and drogue position by measuring azimuth and elevation angles from the EO grid transmitter to multiple EO grid detectors (Fig. 4). Slant range is formed from the azimuth and elevation angle measurements to two or more detectors having known physical separation. A common navigation point (CNP) is computed in tanker body–relative spherical coordinates. The spherical CNP location can then be transformed to tanker body–relative Cartesian coordinates that is shared with each receiver (aircraft and drogue) via a data link. This provides a short range wireless local access network to ensure the continuity and accuracy of navigation solutions. The data link can additionally provide command and control (C2) and situational awareness. Flight tests in 2009 using a K-707 tanker with refuelling drogues mounted with EOGRS detectors were reported by the company to be successful in providing high precision motion and position data [119,120]. Critically the absence of GPS will make the technique available in GPS-denied scenarios.

3.6. Sensor fusion

These systems are mostly restricted to either near or far position estimation. MV and GPS systems lend themselves to near and far position estimation respectively but neither system is capable of operating sufficiently across all the required refuelling tasks. The use of laser-based systems may be applicable to both short and long-range finding, however attenuation from water, or other particles in the air over long range may be a limiting factor.

MV systems work most accurately when more information is within detectable range of the associated camera arrangement, and have been demonstrated with high fresh rates suitable for high bandwidth control. One obvious limitation with GPS measurements is that pose cannot be conventionally identified solely from GPS data. The significantly poorer update rate is the main limitation in its use for close proximity estimation however the accuracy of GPS, whilst somewhat less than an MV system, is constant across the entire operation, and is not dependent on a visual target.

A two stage approach using (1) GPS when the receiver is far from the tanker and (2) vision-based sensing when the receiver is sufficiently close to the tanker has therefore been proposed in several works. Researchers in the universities of Perugia (Italy) and West Virginia (USA) developed a combined MV–GPS based sensor system for AAAR, using a fusion filter based on the UAV–tanker distance, integrated into a docking control scheme [60,61,121]. As the receiver approached the tanker the system transitioned from GPS to Machine-Vision (MV) measurements, using full MV feedback at small distances. In [122,123] Mammarella et al. explored integrating a sensor fusion technique using an extended Kalman filter (EKF) with position measurements supplied by both the MV and GPS sensors, with results showing more than one order of magnitude improvement in the precision of position estimates as opposed to individual systems. Additionally the EKF sensor fusion system had desirable robustness characteristics. Similarly Williamson et al. [124] employed an EKF, using both GPS or electro-optical sensors (individually however, not in parallel) to correct the inertial navigation state of both the receiver and tanker aircraft. Including both of these adds additional redundancy to the system. Two methods for fusing the GPS and inertial data were explored (1) a filter which estimated the state errors in both vehicles and (2) a reduced-order filter that only estimated the relative state estimates. Under high dynamic conditions, at the expense of computation power, the EKF offered improved accuracy for the estimates. Results showed that using a combination of either GPS/INS or GPS/INS/EO the relative position error was maintained within 10 cm in each axis, within that typically needed for a successful capture.

The work in [124] assumed that the receiver transmits information to the tanker which performed the sensor fusion process to provide the high-accuracy estimate of the receiver's receptacle location for the tanker boom controller. However the information flow could easily be reversed and the fusion performed by the receiver for position tracking relative to the tanker or a drogue. It is also worth noting that, in detecting and tracking a drogue or receptacle, the MV will not provide any useful information once engagement has been made hence any fusion system should switch to another estimation method to maintain a fixed relative distance between the receiver and tanker. In some works this was GPS measurements however it could be (and perhaps more reliably be) a similar MV system utilising feature recognition on the tanker.

4. Control strategies

There have been extensive studies on appropriate control systems suitable throughout, and for different stages in, the refuelling operation. There are three distinct control tasks for controlling the receiver through the refuelling process: (1) *trajectory generation* and following for rendezvousing, (2) *regulation* to the static relative waypoint positions around the tanker, and (3) *tracking* the drogue or receiver's refuelling port.

Before the turn of the millennium there was little interest in studying automatic control for air to air refuelling. Trosen [125], and later with Pachter and Houpis [126], developed a regulator based on Quantitative Feedback Theory (QFT) [127] for designing an automatic station-keeping flight control system (FCS) for the USAF. The primary purpose was to alleviate manual control rather than instigate levels of autonomy for UAVs. A simple outer loop feedback controller was designed to achieve station keeping in the presence of wind gusts and fuel transfer dynamics. QFT was used in order to realise a controller that would be robust enough given an amount of uncertainty assumed in the models of their aircraft.

4.1. Linear control techniques

Interest in UAVs has subsequently escalated over the last twenty years which has led to a wealth of proposals for automated refuelling control systems. Most of these combine some form of integral control required for zero steady state error tracking. Valasek et al. [95] argue that both stability and performance robustness are required in any controller designed as it must operate in the presence of uncertainties, mainly due to the atmospheric turbulence. Modern design techniques are well suited to provide stability, and in some cases, robustness guarantees but at the expense of practicality and design transparency. In most cases the principal task in AAAR can be seen as a docking problem [61] where the receiver (or boom) needs to track the trajectory of the drogue (or receiver, in flying boom operations). Therefore the design of trajectory generators also appears in the literature.

Control work for Texas A&M's VisNav system focused around the integration of a proportional–integral tracker coupled with a regulator that offers guaranteed steady-state convergence and a pre-filter on the control commands to limit the effect of exogenous inputs [96,97]. A full-state feedback linear quadratic method was then used to populate the gains on the argument that all of the fundamental feedback states on an aircraft are easily measurable. Note however that this would include measurement and feedback of the control positions which, whilst not impossible, is not typical in practical designs. As the regulator is optimised according to a quadratic cost function that relates to the infinite horizon algebraic Riccati equation stability is guaranteed and the designed gains always provide a stable solution, only effecting the transient performance of the system. A Kalman filter was used to further filter out external disturbances and measurement noise and estimate unknown states. Results show that their controller was able to guide the probe into a stationary drogue for successful docking even in the presence of moderate turbulence. The full control system was seen to demonstrate good disturbance rejection and all states and controls movements were found to be within acceptable limits. A stability and robustness analysis of singular values showed the controller satisfied high frequency stability robustness criteria. However it was not able to satisfy robustness criteria at lower frequencies due to a high sensitivity function as a consequence of timely transient performance [97]. The work in [53,54] also makes use of this control structure for control and docking of a flying boom with a station-keeping receiver.

A command generator and tracker was added in [111] to accommodate a moving drogue model in which a reference trajectory is generated by a model of the drogue with known inputs. The main drawback with this approach is that the position or trajectory of the drogue must be known and an accurate model of the drogue dynamics is required to accurately estimate its motion. The paper by Tandale et al. [128] overcomes these deficiencies by presenting a reference-observer-based tracking controller which does not require a drogue model or *a priori* knowledge of the drogue position. With the reference observer estimating the open-loop feedforward control and the reference states that the receiver aircraft is able to track a reference trajectory generated onboard in real time.

Elsewhere Ochi and Kominami [129,130] devised a proportional navigation law with line of sight angle control after noting similarities between docking and the missile guidance task. Kim et al. [131] made use of the receiver dynamics modelling in [10] to implement a gain scheduled controller based on a combination of integral control and optimal LQR design with emphasis on tight position control during racetrack manoeuvres. This was then later extended in [132] with the proposal of using an unscented Kalman filter to estimate the receiver states and wind vectors. Fravolini et al. [60] used a multivariable H_∞ design method for a controller to track a trajectory generated by a fuzzy fusion system combining the measurements from GPS and MV systems. In a comparative study Murillo Jr. and Lu [133] compared three time-domain control design methods for regulating the position of a simplified F/A-18 model. In using a simplified model, robustness is a necessary requirement in the design methods to compensate for the inevitable modelling uncertainties. Preliminary results indicated that between a robust servomechanism and a model-following design (both populated using LQR) the transient performance and corresponding control effort were similar but with a slightly superior performance from the simpler servomechanism design. A mixed sensitivity H_∞ design also tested was also able to track commands but exhibited poor overshoot and settling times. Since all of these methods can provide adjustments to a design in the form of weighting matrices and functions, further tuning may have reduced the performance gaps encountered.

4.2. Nonlinear control

In using optimisation methods it is important to accurately formulate the problem in order to optimise the response about the desired state and achieve a satisfactory result. One of the limitations with LQR, H_∞, and the other linear optimisation techniques is

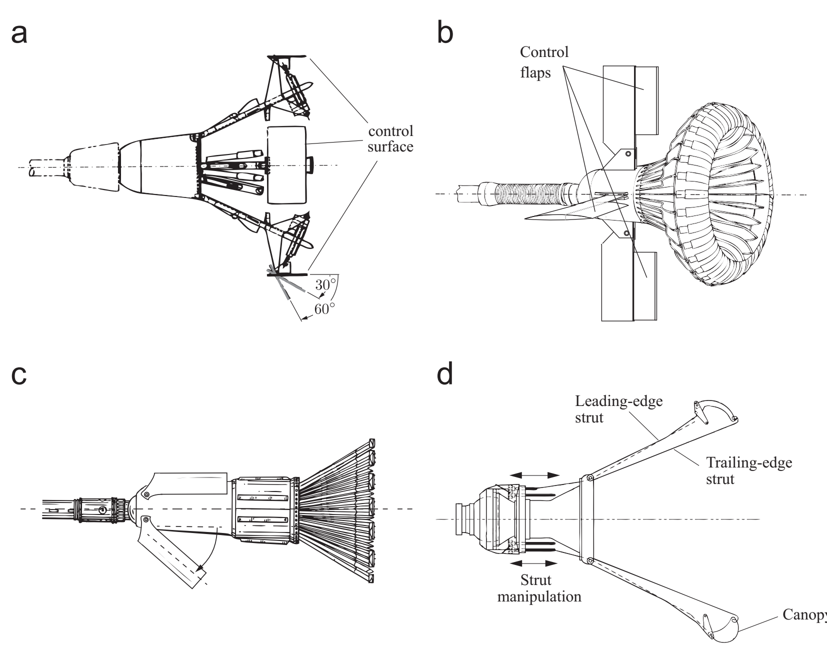

Fig. 5. Controllable drogue concepts. (a) Strut-mounted control surfaces [145]. (b) Mid-section flaps. (c) Spoilers. (d) Canopy manipulation. Image adapted from [151].

that nonlinearities such as rate limiters and saturations are not well handled. The benefits of implementing a nonlinear control law include obviating gain scheduling and accommodation of potential higher order nonlinear effects. Elliot and Dogan [134] conducted a preliminary investigation in the design of an input–output feedback linearisation (IOFL) scheme for an AAAR system. Instead of computing Lie derivatives, linear equivalent matrices were investigated at given conditions which helped in understanding the nature of the influence of the control variables selected. Initially airspeed and relative position were selected however this led to a non-minimum phase system which, although it can provide tracking, leads to internal instability in a conventional feedback linearisation formulation. A similar consequence resulted in attempting to control orientation angles, whereas a stable solution resulted from controlling the airspeed with attitude rates. Consequently an augmented form including both rates and relative position was adopted and demonstrated. Thus in order to realise such a controller an outer loop command and trajectory generator was required to transform relative position error into commands for the augmented variables in the inner loop IOFL design. Controlling relative position directly in the control structure should be possible by adopting Global Stabilisation or Back-Stepping methods [135] in conjunction with an appropriate Lyapunov function which guarantees stable dynamics [136].

4.3. Adaptive control

Reliable performance and safety will be a strong requirement in an AAAR system. One way of improving the reliability of capture performance is to adopt adaptive control techniques. However adaptive control problems are formulated for the infinite horizon whereas guidance problems are characteristically finite time problems. This presents a major challenge when implementing adaptive control techniques to optimal control problems. Stepanyan et al. considered using differential game approach and adaptive control techniques in the design of autopilots [137,138]. Although the results were preliminary and in a relatively low fidelity simulation environment they are certainly promising and pave the way for more detailed studies. Wang et al. [139] explored a $\mathcal{L}_1$ neural network based system for controlling the AAAR problem. State feedback with integral error control was used to stabilise the closed-loop plant in a disturbance-free environment before the adaptive controller was designed and implemented to compensate for wake vortex effects, leading to the desired transient performance with a guaranteed stability margin. In later works [140] they employed the controller on the more complicated BANTAM configuration and a more detailed wake model to further verify the controller's capabilities and included uncertainties in control effectiveness such as actuator failures [141,142]. Simulations of increasing magnitude of the wake vortex effects showed a scaled response by the adaptive controller corresponding to the changes in the disturbances. Purported benefits of their approach are a systematic design theory, and the achievement of uniform smooth transience for both system inputs and outputs simultaneously.

Compensation for control effector failure was also the principal task in [143] where an adaptive fault tolerant controller capable of handling control effector failures without an accurate knowledge of the receiver or the drogue dynamics, or knowledge of control effector failures was devised. The structured adaptive model inversion (SAMI) controller did not depend on fault detection information, yet demonstrated smooth trajectory tracking and probe docking in the presence of control effector failures and uncertainty introduced in the controller design owing to parameter variation in the aircraft model.

More recently in [144] Wang and colleagues presented further work for time-varying reference systems. They attempted to use the adaptive control techniques to a gain-scheduled baseline controller. Through the use of adaptive augmentation they attempted to satisfy two main points: firstly, the augmentation must be able to recover the nominal performance of the baseline gain scheduled controller at different operating points without compromising the performance of the gain scheduled controller. Secondly, in the absence of uncertainties the output of the adaptation must be zero. They analysed the stability and performance of the resulting adaptive controller for a time-varying closed-loop reference system, showing that the rate of adaptation can be increased uniformly in order to retain the performance of the gain scheduled controller. Racetrack manoeuvres were implemented to illustrate the application of adaptive augmentation. Their adaptive controller has the benefit of guaranteed performance bounds similar to that for linear time-invariant reference systems, and slower rates of variation for the scheduling variables used in baseline controller design are also not required for the stability of the adaptive augmentation.

4.4. Drogue stabilisation and control

The passivity of the hose and paradrogue system makes it particularly susceptible to external disturbances and exacerbates its capture. There is now growing interest in affording it a level of control that the flying boom method currently benefits from, for which a few possible means have been explored.

As with the flying boom, control surfaces offer an obvious method of generating control forces on the drogue. This idea was originally investigated back in 1977 [145] with a considerably draggy frontal arrangement of remotely operated control surfaces that replaced the canopy (Fig. 5a). Although directed movement was achieved in flight tests, unexpected rolling motion was believed to be due to a combination of the trailing wing vortex and an induced rolling moment from the flap deflections. The design resulted in a need to achieve constant drag to maintain altitude which led to a cumbersome cross-control system of the flaps. The idea of a controllable drogue did not seem to be developed further until much recently, where Ro, Kamman, and Kuk [146,147] presented simulations and wind tunnel tests of a cruciform arrangement of aerofoils connected to the drogue receptacle (Fig. 5b). Here the flaps were controlled by acceleration feedback via a manually tuned PID controller. Their simulations indicated an almost complete reduction in turbulent drogue motion, though in wind-tunnel tests (with a 1/3-scale drogue) they achieved a more modest stabilisation. A similar study by Thompson [148] presents wind tunnel data for a half-scale drogue, comparing force generation via control surfaces and spoilers (Fig. 5c). Integration with existing systems would prove challenging however, if the drogue is required to collapse for stowage.

Meanwhile Francis [149] used spoilers in a triangular configuration to create control forces. Thompson [148] also investigated a single spoiler arrangement which indicated a level of achievable lateral control force but with a correspondingly significant increase in drag. A spoiler-configured drogue would likely be easier to stow than using mounted control surfaces due to the mechanical ease in collapsing the flaps flush against the drogue.

A less orthodox approach was proposed by Williamson et al. [150,151] involving manipulation of the drogue canopy in a manner to alter the aerodynamic forces (see Fig. 5d). By varying the angle between the leading and trailing edge strut arms the local centre of pressure on the struts is altered, generating forces of the order of 300 N at 130 m/s airspeed. Wind tunnel testing of a drogue, with four actuators in a cruciform configuration, was used to generate an aerodynamic model. Results show that nearly linear vertical and side forces were generated with low bandwidth actuators shown to supply sufficient force for this process. The aerodynamic model was then amended to a hose–drogue simulation model to assess achievable lateral and vertical offsets from the steady-state position. They developed a feedback control algorithm via LQR, using position, measurable for example via differential GPS (DGPS), and acceleration, possibly via an inertial measurement unit. Stabilisation under the effects of wind, receiver forebody effects, and disturbances was demonstrated to within 5 cm.

Other elaborate methods that have been devised include gyroscopic-regulated control induced by a rotating mass coupled with an air turbine located in the drogue assembly [152] and thrust-vectoring techniques [153,154].

4.5. Multi-agent mutual control

With an increasing number of autonomous agents involved in the control scenario the number of possible system states quickly grows unmanageable if the system is to be supervised in a top-down manner, especially by a human. Consequently there is a need for a more efficient means to supervise the system, and also to better interconnect the decision-making capabilities of each agent so that tasks are approached coherently rather than by individually programming each agents' behaviour. This requirement has led to the field of *cooperative* (i.e. behaviour-based) control, where groups of interconnected, decision-making agents interact with locally sensed information to solve a specific objective [155].

This ideology has been applied to the general aircraft rendezvous and formation flight tasks: [156,157] for example. McFarlane et al. [55] utilised a low-level cooperative scheme in order to manoeuvre a refuelling boom and F-16 towards the centre of a refuelling envelope in concert. To do this a target location was generated as a function of the locations of the F-16, refuelling boom, and refuelling envelope centre (fixed relative to tanker). Instead of the F-16 tracking the centre of the refuelling envelope and the refuelling boom tracking the F-16 they both now track the target location. The cooperative control loop is realised via a target point function which takes a weighted average of the positions of the F-16 and refuelling boom tip, before being passed through a PID controller to yield the position for both receiver and boom to track. The target point function had to include the relative location of the refuelling envelope otherwise the target point drifted away from the refuelling envelope centre. Assuming that the methods for drogue stabilisation can be successfully extended to enable positional control, then such cooperative control methods could equally be applied to a probe and drogue system.

The notion of cooperative control is strongly related to the concept of *collaborative* control which developed from the traditional supervisory relationship between a human operator and a teleoperated (i.e. remote controlled) machine. In a collaborative system, rather than being the operator, the human is treated as another information source for the artificial agent(s) who work(s) as an equal peer, querying the human for relevant data to carry out its task. The artificial agents are still subordinate to the human operator but only in terms of higher-level commands, goals, and tasks. In this way the agents can be more adaptive, and better able to accommodate varying levels of autonomy [158]. This provides a defence against human error wherein an agent can follow decision protocols to evaluate the quality of human inputs and avoid following commands that would otherwise place itself or another agent in danger. Ding et al. [159] pursued a mathematical framework for this using reachability sets to design the transition conditions and timings of the aerial refuelling sequence, including detection of unsafe manoeuvres and the appropriate times for fallback manoeuvres, all within time and safety constraints.

Etymologically there is little difference between the meaning of 'cooperative' and 'collaborative', though in a control context 'cooperative' is frequently associated with swarms of similar robots whereas a 'collaborative' system seems to typically have one of the agents as human. A further term, *intimate* control, was used by Griffiths [160] to describe a method for mutual docking with an unmanned ground vehicle (UGV). Griffiths states that the full capabilities of the two docking agents (UAV and UGV) are frequently under-utilised and proposed a controller 'to allow the agents to exploit their respective capabilities to the full to meet the docking constraints'.

For any such control strategy there is a requirement for mutual information transfer between the agents, and for application to AAAR this would require robust and secure data links. However it is possible that using such a control scheme could provide a tighter tracking and a more robust control solution for the docking procedure [161].

4.6. Rendezvous scheduling

Prior to the docking task the receiver must first rendezvous with the tanker in a timely and safe manner. Research has also been conducted on this problem in what is primarily a trajectory generation and following problem. Burns et al. [162,163] proposed a feedback controller in order to guide the receiver to the rendezvous point whilst meeting imposed restrictions on heading and speed by using a geometric approach to predict the location of the rendezvous point. The controller was designed to adjust acceleration commands whilst turn rates were restricted. A geometric waypoint estimator along with a collaborative autonomous rendezvous controller was used to generate the heading rate and acceleration commands by using a heading and a time-of-arrival control loop. The geometric waypoint estimator used an algorithm to generate the optimal Dubins path [164] to the rendezvous point and two navigation waypoints along with path distance and time to intercept were also estimated.

A dynamic inversion controller was used in the heading controller in order to navigate to a series of waypoints. In order to account for actuator dynamics, the commanded turn rate was passed through a low pass filter. A predicted turn point was calculated at each time step until the turn point was at a range of 1.5 times the radii, at which the controller switches the target point to the required turn point. Depending on the inputs from the time of arrival controller, the radii of the Dubins path arcs are allowed to vary as the turn rates are limited by the time of arrival controller.

They also attempted to minimise the fuel consumption by minimising the time required for the receiver to rendezvous with

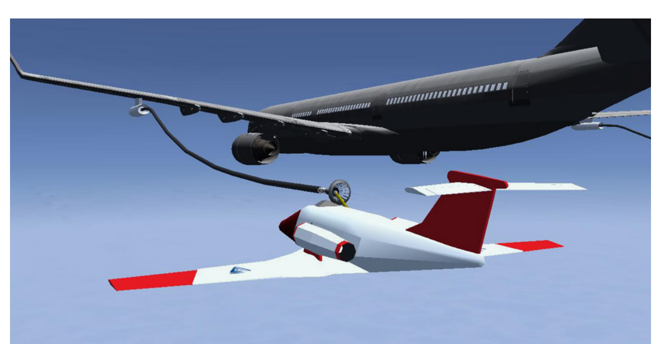

Fig. 6. Probe-and-drogue refuelling simulation.

the tanker. With the tanker and receiver approaching each other, the rendezvous controller was able to avoid their collision but unable to successfully rendezvous with the tanker. In [162] it was suggested that with an arbitrary heading, in a corridor with four-turn radii on either side of the tanker's trajectory, rendezvous is highly unlikely; the corridor reduces to two-turn radii on either side when the heading is limited to the opposite direction of the tanker. Numeric dynamic optimisation techniques were used to numerically calculate the optimal trajectories for the rendezvous case. Rendezvous times were very similar to the rendezvous controller and the optimisation with a fixed velocity (about 3% difference) whereas there was about 14% variation when compared to a free velocity optimisation.

Smith [165] presented a Proportional Navigation (PN) system with adaptive terminal guidance together with a coupled velocity controller developed for a constant altitude UAV–tanker rendezvous. The command turn rate for the UAV receiver was kept proportional to the rate of change of the line-of-sight between the receiver and the estimated rendezvous location. Smith also applied similar limits to the turn rate, velocity, and acceleration in the PN controller. To prevent prolonged tail chases, the PN controller was configured to fly the receiver to the location where the tanker is predicted to reach in the future using a rendezvous point estimator. With each update, the estimator predicts a new rendezvous point based on current measurements of the tanker position. Smith suggests that although the rendezvous point is just an estimate, the estimate will become increasingly accurate as the receiver gets closer to the tanker, finally coinciding with the tanker location. Knowledge of tanker path and geometry would also assist in accurate prediction of the rendezvous point even in the presence of the tanker wake and wind disturbances.

In [166] Kampoon et al. addressed the issue of prevailing wind, proposing a 'point-parallel' rendezvous process where the tanker aircraft flies along a racetrack while the receiver aircraft enters the refuelling area at a fixed point. In the absence of wind this is easily attainable however a horizontal prevailing wind will tend to distort the actual flown racetrack pattern relative to the inertial frame. In order to overcome this effect they introduced a virtual target, free from wind effects, capable of flying in a geographically fixed racetrack. The tanker used a nonlinear guidance algorithm to follow the virtual target in the refuelling orbit whilst a lateral acceleration-to-yaw rate regulator and proportional speed controller was employed to ensure that the tanker tracked the virtual target.

Fig. 7. The University of Bristol Relative Motion Robotics facility mounted with probe and drogue equipment.

5. Simulation and testing

5.1. Virtual environments

By combining models for the topics discussed above in an integrated manner a comprehensive simulation model can be created for testing and simulating a wide variety of scenarios with technology and control concepts. Ideally these types of wholly software based simulations incorporate the highest possible fidelity so that statistically reliable results can be obtained [167]. Various works have amassed, over time, representative models for the receiver aircraft (the tanker most often treated as a moving point mass), dynamic cables for a hose with an aerodynamically representative drogue, pivoted beams for a flying boom, and the airflow effects from the tanker's vortex wake field and receiver's bow wave. Others have included models for the GPS systems [124], and air data and inertial measurement units [168]. Simulink is frequently the computational software of choice. In [169,170] Simulink code was compiled and run inside the off-the-shelf DynaWORLDS package to visualise the refuelling simulation. Other options for visualisation include Simulink's own 3D animation toolbox based on VRML [171], X-Plane, or FlightGear (Fig. 6).

5.2. Robotic facilities

The testing and evaluation of sensors is greatly aided by the physical link provided by a hardware-in-the-loop (HIL) facility. And given the high dynamic environment a real-time simulation (or as close to as possible) is needed to effectively replicate the refuelling scenario for sensors to be accurately tested. The cost of such facilities has prohibited their use, however, whilst research institutes with the opportunity have expended effort into actual flight tests.

Pollini et al. [99] used a relatively small KUKA KR-150 manipulator to replicate flight dynamics whilst capturing images of aircraft-mounted LED beacons as markers for the pose estimation algorithm. Common infrared LEDs typically emit the light with a wavelength between 850 and 950 nm making a standard off-the-shelf CCD cameras (most of which can detect up to 1100 nm) sufficient for detecting the markers, after applying a low-pass filter to remove light below 700 nm, and calibration to remove distortion around the pixels identified with the markers. The HIL facility in [124] was designed to simulate boom–receptacle aerial refuelling and the rig consisted of one-eighth-scale model of the aircraft (F-16) and the refuelling boom. Two motion control systems were used: one to move the aircraft in three axes of translation, and another to extend and pivot the boom to change the boom elevation and azimuth angles. A receptacle capable of interconnecting with the boom was installed in the aircraft model and an IMU was used as the primary sensor for relative navigation. Use was made of wireless communication to easily share the position information computed by the IMU to other parts of the facility without the physical restrictions of wires.

More recently a sophisticated testing facility has been developed at the University of Bristol in the form of a Relative Motion Robotics (RMR) facility [172,173]. The facility was principally devised for hardware-in-the-loop testing for cost effective research trials for evolving aerial refuelling technology (as shown in Fig. 7). However the RMR is also capable of investigating wider technology exploitation and utility to industry and academia for relative motion work [174]. Unlike the previous works in [99,124] which used reduced scale models, the RMR facility employs two manipulators capable of supporting full-size refuelling apparatus, along with the capability to integrate pose estimation systems into a real-time control loop. In doing so the suitability of vision

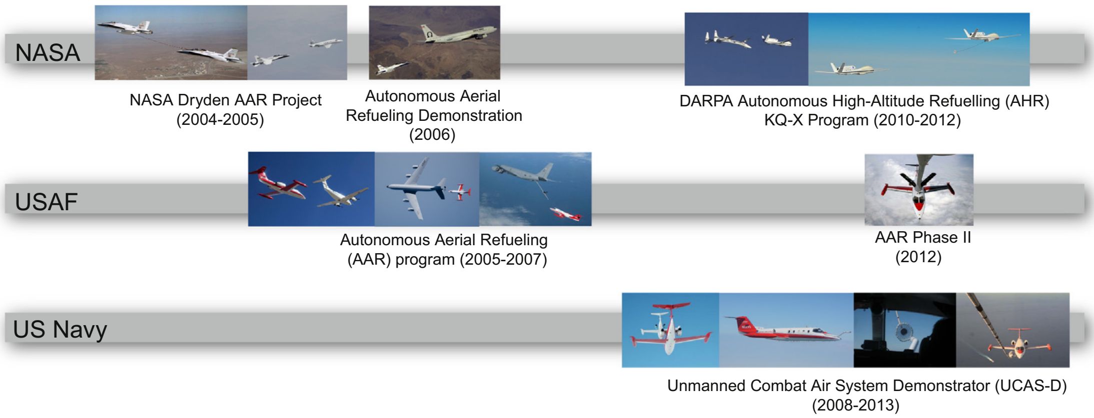

Fig. 8. Timeline of AAAR flight test demonstration programs.

systems, tracking algorithms, control system designs, and refuelling hardware that are mature in their development can be tested.

Simulations are written in the Simulink environment and compiled with the Simulink Coder toolbox for use on the PXI platform using National Instruments Veristand target language compiler. Simulations can cover the wider refuelling scenario in order to develop and investigate control strategies, with the RMR specifically providing the HIL capability for the more complex hookup space. The real-time operating system is capable of overseeing the deterministic execution of multiple models, or processes at defined rates. The primary control loop executes the simulation model and the supervisory process in turn, both at a 1 kHz rate. Compared to flight tests, the RMR facility has the important advantages of less lead time, reduced cost, safer operation, and guaranteed repeatability.

5.3. Human–machine interfacing

Comprehensive simulation environments also are a key enabler for training of human operators that will be required in any first generation AAAR capability. Work in [175] describes the work on developing a prototype control station and interface for managing multiple UAV receivers in a refuelling operation. AFRL's Aerospace Vehicles Technology Assessment and Simulation (AVTAS) laboratory can simulate a human-in-the-loop refuelling scenario using simulation consoles for a boom operator, tanker pilot, and UAV operator. The entire simulation is directed from a primary control station and can be observed by experts or examiners from another dedicated observation console. Commercially available D-Six simulation software is used, with 21 workstation PCs linked via ethernet using the SCRAMNet reflective memory network. D-Six is used to simulate the vehicle aerodynamic models and the vehicle dynamic states, with logical and discrete data fed into an I/O control PC via SCRAMNet. Audio sounds and cues taken from actual KC-135 boom operator station are generated and the communication lag between the operator and the UAV can also be modelled. The vehicle state data can be supplied to the boom operator station and UAV operator station via ethernet for image generation and heads down display generation. In [176,177] AVTAS was used to create a synthetic scenario of a KC-135 servicing four UAVs to investigate display interface concepts and identify issues affecting the operators ability to safely accomplish the AAAR task.

5.4. Flight testing and demonstration

Simulation environments are superior in providing repeatable testing conditions. However when the environment (in this case aircraft flight) is highly complex and uncertain it is impossible to fully recreate it in simulation so flight tests must be pursued to further evaluate solutions to particularly complex problems, and in most cases, provide a final evaluation of a design in the target environment. It is perhaps not surprising that the USA has led the way in practical demonstrations of AAAR. The USA's autonomous refuelling programs to date are summarised in Fig. 8. As of the time of writing NASA's AARD project is the only program that has demonstrated actual physical connection using AAR apparatus.

Over the course of several years since the turn of the millennium the US Air Force Institute of Technology (AFIT) has been developing a variety of technologies for autonomous refuelling, including sensor requirements [81] and formation flight control systems [178–180]. In order to demonstrate the performance of such a flight control algorithm in an operationally representative environment, formation flight tests were conducted at the USAF Test Centre, Edwards Air Force Base. A USAF C-12C and a Calspan Variable Stability Learjet LJ-25 were used to simulate a boom–refuelling tanker and the unmanned receiver respectively, with both aircraft fitted with a data link antenna and transceiver, GPS receiver, PC-104 computer DGPS software, and a laptop display. Additionally the tanker aircraft was equipped with a MEMS IMU and the receiver had software installed in the variable stability system and a pilot display of current and commanded positions mounted on the instrument panel. The flight controller was able to keep the receiver aircraft well within the simulated boom envelope in the contact position as well as within safe position tolerances during the pre-contact and wing observation positions. During 15° and 30° bank turns, satisfactory station keeping was demonstrated in all three positions (wing observation, pre-contact, and contact). However in the contact position large lateral position errors were observed during rapid rolling manoeuvres which would have led to disconnection and possible boom fracture during the refuelling operation. Rolling motion was tested up to 12 deg/s which was acknowledged as somewhat larger than the typical 3 deg/s to 15° bank of a typical refuelling track. This work led onto the 2006 demonstration between Boeing Phantom Works and the USAF Air Force Research Laboratories (AFRL), demonstrating autonomous station keeping of the Learjet surrogate UAV behind a boom-equipped KC-135R tanker. The refuelling position was reportedly held for just under 30 min while the tanker flew two refuelling patterns. Final flights in 2007 demonstrated autonomous transitions between refuelling positions, from rendezvous through contact and breakaway [181]. A second phase to the project was initiated in 2009, with further simulation work and more focus on developing the precision GPS and alternative onboard navigation systems. Flight tests for these systems, again using the surrogate Learjet, were undertaken in 2011, to evaluate upgraded sensors and improved relative navigation and positioning software [182].

Continuing the work previously achieved in [76–78], NASA's Autonomous Airborne Refuelling Demonstration (AARD) project continued in 2006, involving the development of analytical models, and demonstration of an automated aerial refuelling system. They principally used two F/A-18B aircraft and a Boeing 707-300 aircraft, configured for probe–drogue refuelling [183]. The Boeing 707 was modified to include a GPS antenna and a data-link antenna with a computer installed to measure and transmit the GPS/INS data to the receiver aircraft. A NA-265 Sabreliner was used as a surrogate tanker in June 2006 to test the navigation and station keeping systems in order to increase flexibility in the schedule as it had a lower flight cost per hour and was easier to schedule than the Boeing 707 [183]. For take-off, landing, and transit to and from the refuelling condition, the receiver F/A-18 was flown manually by a pilot. Only the approach and capture modes were flown by the autonomous controller, designed and developed by Sierra Nevada Corporation. A camera tracking system was employed consisting of a single camera mounted on the cockpit of the receiver aircraft, connected to a commercial off-the-shelf video tracking processor. Several test flights were flown to test the performance of the AARD system which was shown to be capable of following the tanker aircraft through turns whilst maintaining a relative position. During the final flight, several attempts were made to capture the drogue, with a 33% success rate. Even during the missed attempts, the AARD controller was able to retreat the receiver aircraft from the drogue in a controlled, safe, and predictable manner. Phase 2 of the program carried through October 2006 to April 2007 with the purpose of developing the rendezvous systems, improving controller and optical tracker performance, and investigating capture of the drogue in a refuelling turn. The phase ended with successful capture in both a refuelling turn and moderate levels of turbulence [184].

Continuing this project in 2010, Northrop Grumman led a $33 million DARPA-funded program (KQ-X) investigating and developing autonomous aerial refuelling techniques for HALE UAVs, using two NASA Global Hawks. The KQ-X program ran initial risk assessment flight tests in January 2011 which looked at the wake effects for receiver and tanker in close separation, both autonomously controlled [185]. This was conducted with a Global Hawk and Northrop Grumman's Proteus high altitude tandem-wing vehicle. Both vehicles were operated at 45,000 ft and achieved a minimum distance of 40 ft [186]. Later operational tests utilised two Global Hawks with a somewhat unorthodox formation (the tanker vehicle flew aft in the refuelling formation) in early 2012, which further tested close formation holding and hose retraction systems [187]. It successfully completed a two-and-a-half hour formation flight maintaining less than 100 ft between the refuelling probe drogue [188]. Further tests were originally planned for the summer of that year but were reportedly cut short because of configuration time needed to repurpose the Global Hawks for NASA's hurricane tracking flights in September [189]. Nine flights in total were made in the project.

A US Navy-based program started in earnest in 2008 to develop and demonstrate an autonomous refuelling capability for Northrop Grumman's X-47B UCAV, via both boom and drogue refuelling systems [190]. This was part of the Navy's Unmanned Combat Air System Demonstrator (UCAS-D) for aircraft carrier-operated combat UAVs. It also shared some resources and operational aspects with the second phase of the USAFs AAAR project. In order to mature the refuelling technologies alongside the initial autonomous approach and landing tests, the autonomous refuelling systems were developed and tested on the same type of Calspan surrogate Learjet used previously with the AFRL AAR project. Flight tests began in 2008 to demonstrate autonomous closed-loop rendezvous and station keeping, around both the tanker and drogue equipment [181]. Later tests in 2011 and 2012 saw a prototype version of the X47B flight control hardware and software integrated with the surrogate platform. The Learjet, commanded remotely from a ground operator, completed multiple refuelling test points around an Omega K-707 tanker [181,191]. These tests successfully demonstrated fully autonomous control from rendezvous to contact, then breakaway, with the X47B systems. The latest tests in 2013 deployed flight-qualified X-47B hardware into the Learjet, and flight tests were performed with a newly installed refuelling probe. Tests in 2014 are expected to work towards demonstrating the requirement for both boom and probe-and-drogue refuelling methods. However these tests may not be performed on the actual X47B vehicles due to fiscal budget cuts [192], and instead continue to make use of the Learjet surrogate.

In each of these projects surrogates, as both tankers and receivers, have played an important part in progressing the research despite budgetary and scheduling difficulties [193,182]. The AAAR capability of both the USAF and US Navy currently relies on the high-precision positional information obtained from Northrop Grumman's fibre-optic-gyro LN-251 inertial navigation systems [194], which employ significant inertial/GPS coupling, sophisticated GPS-based relative navigation algorithms, and redundant high-speed data links between aircraft.

6. Future developments and research

6.1. Tanker fleets

The number and range characteristics of future receiver aircraft are likely to be the primary drivers of future AAR requirements. The major drivers for future US refuelling needs, reported in [195], are a timely and simultaneous refuelling capability, including that to refuel unmanned vehicles. However it is expected in the next ten years that the total number of tanker aircraft available to NATO nations will decrease following retirement and purchase of more capable tankers with higher capacity (350,000–500,000 lb) and utilisation rates [196]. Dual-capable tankers (carrying both boom and drogue refuelling hardware) would also support a reduction in tanker numbers. They are not however considered an immediately necessary asset but are indicated as the preferred type for future configurations (ultimately however NATO member nations dictate their own tanker requirements). A potential increase in the use of rotary aircraft for maritime environments will drive requirements for 'tactical' (low-speed) tankers. It is also desirable for future tanker aircraft to themselves receive fuel in flight, such as the A400M. This capability will allow more frequent use of the "fuel consolidation" and "force extension" concepts.[1] Tankers may also be pressed into transport, C2 (command and control) and ISR (intelligence, surveillance, and reconnaissance) roles [197]. Consequently they will require threat detection and defensive countermeasure systems if they are operated closer to the battle space. Increasing repurposing of existing civil aircraft, outsourcing operation to the private commercial sector, and tanker formation flight to reduce fuel consumption are also possible developments.

[1] *Fuel consolidation* concerns tanker-to-tanker refuelling for any AAR mission for the purpose of maximising efficiency by redistributing unused or excess fuel, providing a dynamic capability that can be used to react to changing operational and tactical situations. *Force extension* is the concept specifically for increasing the planned deployment range of fighter aircraft by accompanying them with a tanker aircraft, which is refuelled on-route by another tanker, maximising overall range.

6.2. Receiver fleets

Despite newer fighter jets having greater range, their usage is expected to be much greater than previous generation fighters, requiring overall the same level of AAR. Furthermore, as more NATO nations contribute fighters with no accompanying tankers the burden on existing tankers will increase [196].

There has so far been little interest in looking at rotary wing refuelling scenarios, particularly since the recent interest in aerial refuelling modelling has been driven by autonomous refuelling. This is heavily dominated by fixed wing aircraft that are better suited for long range offensive, loitering, and stealth missions for which AAR is best utilised for. However unmanned rotary wing vehicles will no doubt play an increasing part in maritime operations as current manned rotorcraft do. An increase in the availability of tilt-rotor vehicles that can operate in both rotary and fixed wing form will require some consideration of the best type of AAR procedure to adopt (fixed or rotary wing) or modify [197]. Some may be flexible enough to operate with both the 'strategic' (high altitude and speeds – predominately fixed wing) and 'tactical' (low altitude, low speed – predominately rotary wing) depending on their specifications in each form.

6.3. Unmanned refuelling

The key developments for unmanned refuelling will be the development of the sense and awareness and decision making autonomy, integrated into existing refuelling operations and equipment. UAVs expected to benefit from AAR will be of the configuration and scale of existing receiver types: long-range and high endurance fixed-wing vehicles. Reductions in ground-based forces would increase the dependence on responsive air units and encourage the use of persistent loitering UAVs requiring access to aerial refuelling [195].

Small unmanned tankers have the potential to provide the usual benefits of unmanned systems: namely low cost, weight, and removed risk to a human crew. However it is inevitable that some unmanned tankers will be akin to current tankers in the same way future UAVs share common configurations and scale with current manned aircraft. The contentious issue surrounding this is operability with manned vehicles and it has been identified as an area warranting further research [197]. Depending on the difficulties and success of servicing UAVs from manned tankers, a requirement for unmanned tankers dedicated to unmanned systems may emerge. Research into trajectory and flight path management of unmanned tankers for tasks such as fuel consolidation are areas that could be explored.

The passive nature of the probe and drogue system makes it the more appropriate system for autonomous refuelling [196], at least in terms of control complexity. A flying boom configuration would require additional participation from an automated boom controller. A US Army study [198] has gone on to suggest a tanker operating multiple drogue refuelling points in an orbit or track will best serve future unmanned aircraft operations. However, at present, the flying boom is more controllable than a drogue in unsteady air flow, thus potentially offering a greater capture frequency.

Small, low altitude UAVs may also benefit from a refuelling capability but are more likely to refuel from mobile, ground-based refuelling stations [199,200] since tanking aircraft would be unsuitable. Such vehicles are likely to have a significant proportion of electric-powered systems, so the infrastructure for contact charging of batteries could be integrated. Wireless charging of batteries via microwaves [201,202], magnetic resonance coupling [203], or laser-based systems [204] have already been demonstrated at various scales. Potentially these could be developed for the charging of electric systems on HALE UAVs from a tanker with suitably modified hardware.

6.4. Civilian refuelling

In a commercial aviation context reductions in fuel usage for international and haulage flights when using AAR have been suggested to be within the region of 30–40 percent, offering cost savings of similar percentages [205]. Presently commercial airlines will take on enough fuel to either reach their final destination or stop-over, plus an additional safety margin. A significant amount of this fuel is used at take-off to generate enough power to lift the aircraft. Using AAR a lower amount of fuel, sufficient for take-off and part of the journey, can be used instead to significantly reduce the initial take-off weight. The remaining fuel required to complete the journey can then be delivered on-route. The two significant improvements via this method are

1. the overall reduction in power (hence fuel usage) necessary to take-off due to the lower take-off weight,
2. obviating the need to land, and subsequently take-off, for refuelling stop-overs.

Furthermore, by removing the need to stop-over for fuel the overall lifetime of aircraft can be improved by reducing the wear due to landing and take-off per journey. Runway capacity will also be significantly increased due to the absence of stop-over flights. The overall fuel savings, along with the reduction in take-off and landings, would also be a significant contribution towards reducing aviation pollution.

However AAR in a civilian aircraft will be limited by both perceived and actual risk to the public. Pilots will require considerably more training – to a level comparable to military pilots – in the absence of further automation in the refuelling procedure. There are also other reasons for stop-overs including general and essential maintenance and repairs, change of flight crew, the boarding or disembarking of passengers, and providing passenger comfort on long-duration flights.

AAR is more likely to be a factor in civilian UAVs that will become useful in long search and rescue operations, large-scale disaster monitoring and management, and temporary surveillance and communication relaying. Common of these tasks is the need for long endurance which AAR is well suited to provide. In addition to the economic benefits already discussed with refuelling in-flight, the additional time saved from no longer needing to land to take on fuel will provide benefits through improved and extended coverage and eventual savings in total flight time needed. The benefits of electric UAVs are increasing and the prevalent means of recharging these for long-endurance flights is through solar cells. The variety of potential power transfer options previously mentioned could be utilised on such systems, including hybrid-electric vehicles, providing a more robust means of recharging over the current use of solar cells.

6.5. Helicopter aerial refuelling

There has been up to this point very little mention made of helicopter air-to-air refuelling (HAAR). It was first demonstrated in 1965 with a Sikorsky SH-3 and KC-130 and has continued being used for extending search and rescue missions along with supporting special military operations [206]. However there has been little interest in pursuing the topic in the public domain, primarily as the focus has been on AAAR which will be most utilised by long range, fixed wing aircraft. Nevertheless if commercial uses for autonomous search and rescue and other naval activities become viable there may be a desire to have an autonomous helicopter refuelling mechanism which, as is evident by piloted HAAR, comes with its own challenges and specific procedures.

7. Conclusions

Air to air refuelling has been a critical capability for increasing the operational range of military aircraft since the mid twentieth century. Although originally intended to reduce the cost of intercontinental freight transport, the original refuelling techniques were impractical and risky to perform. Modern techniques have been developed to maximise fuel transfer in the shortest time possible, around the capabilities of highly trained military aviators. The implications of close proximity aircraft resulted in years of research into understanding and modelling the complex dynamic interactions between aircraft, refuelling equipment, and pilots. With autonomous aircraft nearing wide-spread service, technology and procedures suited for autonomous systems are now needed.

This means achieving sufficient strides in sensor fidelity and decision-making logic to replace the low-latency and precision of human pilots with at least comparable, if not superior, systems at both high and low levels of control. Consequently the last decade has seen considerable research into these two areas. Key to achieving the sensor requirements will be low latency, high bandwidth, and both precise and accurate spatial measurement. Much research has focused on machine vision techniques, though electro-optical techniques have some promise. The fusion of sensed data from multiple sources, similar to the multi-sensory capability of pilots, is a crucial strategy in overcoming the limitations of these techniques and instil system robustness. An equally impressive wealth of research into flight logic and control has been undertaken. Controller designs range from low level stability and flight control using traditional control design techniques, linear and nonlinear time-domain based control optimisation, and adaptive techniques, to higher level decision-making and rendezvous control logic. Control applies not only to the two aircraft performing fuel transfer, but also other aircraft, how they interact, and the refuelling system including equipment. Improving paradrogue stability and control has also been another research topic of interest.

The performance of these systems both individually and integrated is obviously crucial in order to automate a process that has, to date, been developed with the baseline of a human pilot's cognitive capabilities. Testing in both simulated and experimental operation is therefore necessary to validate and certify these systems. High-capability simulation facilities have been developed in several institutes to prototype designs in the comfort and control of repeatable laboratory environments. Some sensor and control systems designs have already been trialled in both modified manned aircraft and UAVs in flight, with favourable results and verifying the direction of development. To an extent these autonomous systems must comply with currently existing methods and procedures of refuelling to both speed up their deployment, satisfy equivalence for airworthiness certification, and build on a process that benefits from more than half-a-decade's worth of experience. However the use of an autonomous refuelling system should by no means be restricted to existing methods when the benefits of automation can be employed in an altered process. Related to this, the human-in-the-loop aspect should not be overlooked. Since the presence of a human operator or task controller may be a critical, and new, part of the system, human–machine interaction of this fashion, and in this environment, will be another crucial aspect to understand.

We have attempted in this paper to cover the key research trends in a substantial and continually developing area of aeronautics. With increasing costs and reduced budgets, unmanned systems are attractive from an economic as well as a performance point of view, and are likely to become an increasingly larger proportion of military air assets. However changing military needs in terms of tanker numbers, operational requirements, increased airborne persistence, and longer-range strike and reconnaissance platforms may mean changes to the way air to air refuelling is presently conducted. The civilian applications of UAVs are also beginning to emerge. Air to air refuelling can potentially provide economic (and arguably environmental) benefits to such tasks as environmental monitoring, disaster management, and search and rescue. Future reliance on hybrid-electric systems in these vehicles may also lead to a new paradigm of resupply aircraft and supporting infrastructure.

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