

## Advancements in air to air refuelling systems of combat aircraft: A review

Krishnaprasad Vadivelu<sup>1</sup>, Manoharan Ramamoorthy<sup>1\*</sup> 

<sup>1</sup> School of Mechanical Engineering, Vellore Institute of Technology, Vellore -632014, Tamil Nadu, India

\* Corresponding author's e-mail: [rmanoharan@vit.ac.in](mailto:rmanoharan@vit.ac.in)

### ABSTRACT

This review article delves into the progressive advancements in combat aircraft probe and drogue aerial refuelling systems, with a primary focus on various refuelling methods and their suitability for combat applications. The ability to perform air-to-air refuelling is indispensable for both manned and unmanned military aircraft, as it enables them to achieve the necessary operational ranges for the envisioned air wing of the future. The primary contention of this review is to establish the viable and advantageous option of refuelling methods currently available for combat applications, demonstrating its efficacy in enabling strategic combat missions, extending combat range, enhancing surveillance capabilities, and accommodating increased payload. The article explores the intricate details of aerial refuelling probes, which are classified into various types based on their construction and operational characteristics. Furthermore, the autonomous aspects of flight refuelling systems, providing insights into the design and critical operating conditions are discussed. The standard experimental testing conditions are discussed to validate the performance and safety of these systems, shedding light on the technological advancements that have made aerial refuelling an indispensable force multiplier for combat aircraft. The purpose of this extensive review article aims to provide a comprehensive understanding of the state-of-the-art attention towards combat aircraft probe and drogue aerial refuelling systems, offering insights into the latest developments, best practices, and emerging trends in this crucial field.

**Keywords:** combat aircraft, air-to-air refuelling, structural design, flight operations.

### INTRODUCTION

Aerial refueling significantly enhances the operational range and endurance of military aircraft, eliminating the need for frequent landings and reducing fuel consumption by approximately 35–40% [1]. The concept of in-flight refueling was first envisioned in 1917 by Alexander de Seversky, a Russian-American aviation pioneer. By the 1920s, demonstrated this idea using a 15-meter rubber hose and a manually operated valve system [2]. Subsequent advancements in the following decades culminated in the first successful non-stop circumnavigation flight in 1949, showcasing the practical benefits of aerial refueling. Combat aerial vehicles (CAVs) were among the earliest platforms to adopt air-to-air refueling (AAR) systems [3]. Over the past decade, there

has been a surge in automation and system development to support aerial refueling for combat aircraft. Two primary AAR systems are employed globally: the probe-and-drogue refueling system (PDRS) and the flying boom refueling system (FBRS). In the FBRS, the receiver aircraft – typically a fighter jet – is equipped with a receptacle, while the tanker aircraft houses a rigid, telescopic boom. This boom is extended and precisely guided into the receptacle by a dedicated boom operator on-board the tanker [4]. This method requires a dedicated operator, who navigates a telescopic tube into a receptacle of the receiver aircraft [5].

Both refueling methods have their unique advantages and limitations, and the choice between them often depends on the operational demands of a specific military force. For instance, air forces that operate large, long-range aircraft such as

bombers and military transport planes generally prefer the FBRs due to its superior fuel transfer capability. The FBRs can deliver fuel at rates between 2800 and 3000 kg per minute, which is approximately 35% to 50% more efficient than the PDRS [4, 6]. Despite the higher fuel delivery capacity of the FBRs, it is less advantageous when refueling fighter aircraft, as these aircraft are not designed to handle the same fuel transfer rates as strategic bombers or heavy transports. Consequently, the speed advantage of the flying boom becomes less significant in fighter jet operations. Due to this and various operational factors, most air forces and naval aviation units around the world – except for the United States – primarily employ the PDRS.

Aerial refueling is recognized as a critical enabler of extended mission range, reduced reliance on intermediate landings, improved aircraft design efficiency, and overall fuel economy – reportedly contributing to fuel savings in the range of 35–40%. These strategic benefits have made aerial refueling an essential operational capability in contemporary fighter aircraft. Among the various aerial refueling techniques, the probe-and-drogue system is widely adopted due to its relatively compact design, flexibility across multiple aircraft types, and ability to function under

diverse flight conditions. This method also supports the simultaneous refueling of multiple aircraft, although it presents challenges under turbulent atmospheric conditions or limited visibility, where maintaining alignment with the drogue becomes more complex. On the other hand, the flying boom system – characterized by its actuated control surfaces and operation via a boom operator—enables significantly faster fuel transfer rates. However, this method is restricted to refueling one aircraft at a time, due to the size and mechanical complexity of the boom assembly.

The increasing adoption of high altitude long endurance (HALE) platforms, especially in defence-oriented missions, has amplified the demand for advanced aerial refueling systems (AAR). Strategic roadmaps for unmanned aerial systems (UAS) from various nations have emphasized the integration of AAR capabilities to enhance operational range and endurance [7]. In line with this trend, modern combat aircraft are being equipped with different types of refueling systems ranging from fixed air-to-air refueling probes to more advanced retractable refueling probe systems to meet evolving mission requirements and platform versatility. This review outlines the current literature and presents the functional and developmental characteristics of

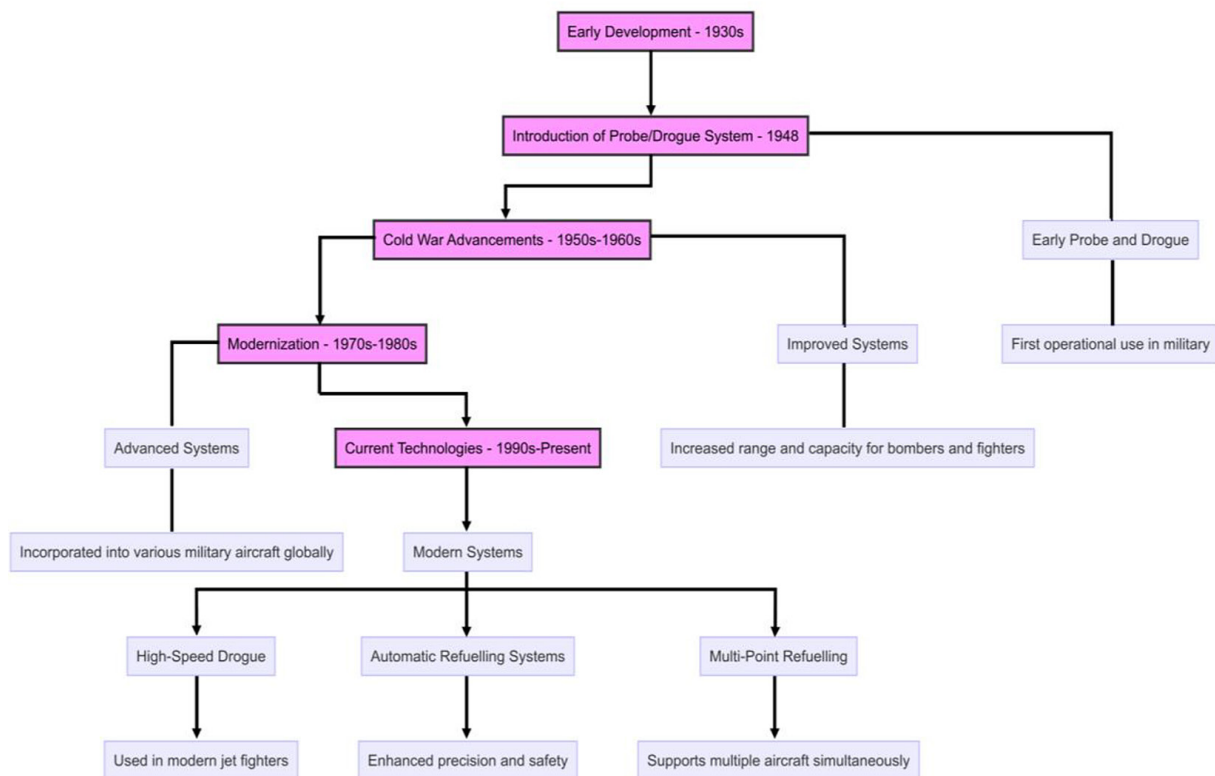


Figure 1. Development of probe/drogue air to air refueling systems

indigenously developed probe-and-drogue refueling systems both fixed and retractable. The schematic illustrated in Figure 1 highlights the progressive development of these systems.

## Methods of refueling

Combat Aircraft employ five types of aerial refueling methods. They are flying boom method, probe and drogue method, combination of refueling methods through boom drogue adapter (BDA), multiple system (probe-drogue and boom systems) and wing to wing system. These methods were evolved and implemented by the military planners based on operational requirements. Currently, the armed forces around the world use either one or more of the following methods: probe and drogue, boom and receptacle or combined methods. The comparison of aerial boom refueling and the probe & drogue systems are illustrated in Table 1 respectively.

## Flying boom method

In flying boom refueling method, the operator from tanker navigates a telescope tube into a receptacle located near the front/spine of the receiver aircraft [4, 6, 8]. A signal is sent to the tanker to begin the refueling process when the boom latches with the receptacle. The pictorial view of flying boom system is shown in Figure 2. The only advantage of this method is higher refueling rate, but the higher refueling rate is balanced by the fact that a single aircraft can only be refuelled at that given time. On the other hand Probe and Drogue systems are capable of refueling more than one aircraft at that instance of given time. In addition, it requires a trained professional Boomer for conducting the refueling operation and it is incompatible with a PDRS [6]. The relative position and control of a receiver UAV from the tanker aircraft with time-varying mass in the refueling phase were studied with the utilization of an inner-outer loop structure [9].

**Table 1.** Differentiating FBRS and PDRS

| FBRS                                                                  | PDRS                                                        |
|-----------------------------------------------------------------------|-------------------------------------------------------------|
| Larger mass, load, and potential cost                                 | Reduced weight ratio and compactness                        |
| Service limited to an individual system                               | Possibility of simultaneous refueling from a single tanker  |
| Refueling of helicopters is not applicable                            | Refueling of helicopters is achieved with low-speed drogues |
| Faster fuel transfer is achievable, but requires a rigid boom station | Simpler to adapt trailing hose with a basket is used        |



**Figure 2.** Flying boom system (boom and receptacle system)

## Probe and drogue method

The Probe and Drogue refueling technique is one of the most widely adopted methods globally. It utilizes a flexible hose deployed from a refueling pod mounted on the tanker aircraft [10–12]. A standard fixed probe and drogue refueling system (PDRS) configuration, as typically integrated into combat aircraft, is illustrated in Figure 3a and b. The probe facilitates safe fuel transfer from a tanker to a receiver aircraft. It is a rigid arm mounted on the forward fuselage of the receiver, positioned based on operational, safety, and visibility considerations. The drogue system, located at the end of a hose, includes a flow-control valve and a funnel-shaped structure supported by stabilizing struts to guide the probe during connection. Refueling pods house the hose and drogue assembly, which retracts fully when inactive.

The refueling pod, or hose drum unit (HDU), consists of a refueling hose, drum, and an end coupling fitted with a drogue [8]. The drogue's deployment and retraction are controlled by a hydraulic system, typically powered by a Ram Air Turbine, either integrated into the aircraft or operated independently. This system regulates fuel delivery pressure, ensuring a stable and safe connection point for the receiving aircraft. It supports various flight conditions such as free flight, initial contact, coupled flight, and disconnection, minimizing unwanted hose and drogue movement. The probe-and-drogue method enables simultaneous refueling of multiple fighters. Modern tankers typically carry three refueling pods – one on each wing and

one on the fuselage. A cross-sectional view of the HDU is presented in Figure 3c [14], while Table 2 summarizes different air-to-air refueling techniques and their applications in combat scenarios.

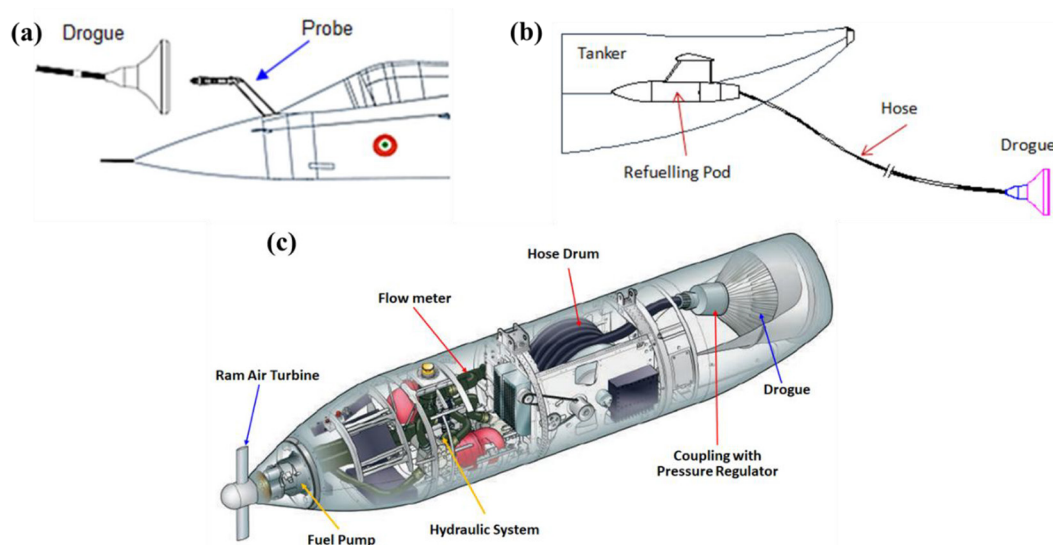
The section highlighted the evolution of aerial refueling methods in combat aircraft, focusing mainly on the Flying Boom and Probe-and-Drogue techniques. The Flying Boom method provides higher fuel transfer rates but is limited to servicing one aircraft at a time and requires a trained operator. In contrast, the Probe-and-Drogue method, though slower, enables simultaneous refueling of multiple fighters and is widely adopted due to its flexibility and compatibility with various aircraft. Comparative tables and case studies illustrate the operational contexts in which each method proves advantageous, emphasizing their complementary roles in modern air forces.

## REFUELING PROCESS BY MEANS OF PROBE AND DROGUE SYSTEM

The following sub-section discusses distinct methods of refueling systems in combat fighter jets and helicopter respectively.

### In-flight refueling of fighter

In-flight refueling of a fighter aircraft from a refueling tanker using PDRS is depicted in Figure 4. The purpose is to ensure the safe transfer of fuel supply from the Tanker plane to the Receiving fighter aircraft by means of a probe and



**Figure 3.** Details of the probe and drogue system and cross-section of the refueling pod [13]

**Table 2.** Methods and inference of air-to-air refueling in combat aircraft

| Method           | Advantages                                                                                                                                                                                                                                                                                                    | Disadvantages                                                                                                                                                                                                                                                                                                                                                       | Inference                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Ref.    |
|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| Probe-and-drogue | <ul style="list-style-type: none"> <li>The probe-and-drogue system offers seamless integration with existing aircraft platforms.</li> <li>Requires minimal specialized training for receiving pilots.</li> <li>Supports simultaneous refueling of two aircraft using dual drogue configuration.</li> </ul>    | <ul style="list-style-type: none"> <li>Features a slower fuel transfer rate than the flying boom system.</li> <li>Demands high-precision piloting for accurate probe insertion.</li> <li>Shows increased sensitivity to atmospheric turbulence.</li> </ul>                                                                                                          | <p>Probe-and-drogue refueling systems are essential for refueling multiple lightweight fighters, despite their slower fuel transfer rate. This system enhances operational efficiency for air forces globally.</p> <ul style="list-style-type: none"> <li>F-16 Viper squadrons use KC-135 Stratotankers for long-distance deployments, extending operational range.</li> <li>Czech Air Force Gripen fighters rely on Airbus A330 MRTT tankers for extended patrols.</li> <li>In the Asia-Pacific, Japan's F-35 Lightning II aircraft use KC-130J Super Hercules tankers for refueling.</li> <li>The German Air Force's Eurofighter Typhoon benefits from A330 MRTT tankers for extended patrols.</li> <li>The Indian Air Force uses IL-78MKI tankers to refuel Tejas LCA fighters.</li> </ul>        | [15–18] |
| Flying boom      | <ul style="list-style-type: none"> <li>The flying boom system offers a faster fuel transfer rate than alternative methods.</li> <li>It ensures a more stable connection during refueling.</li> <li>It reduces the skill requirements for the receiving pilot, making the process easier to manage.</li> </ul> | <ul style="list-style-type: none"> <li>The flying boom refueling method requires a dedicated boom operator and specialized tanker equipment.</li> <li>It limits refueling to one aircraft at a time, reducing efficiency in multi-aircraft operations.</li> <li>The process is complex, demanding precise coordination and advanced technical expertise.</li> </ul> | <p>The flying boom refueling system is highly effective for large aircraft requiring rapid fuel intake. Real-world applications highlight its efficiency:</p> <ul style="list-style-type: none"> <li>USAF F-15E Strike Eagles use KC-10 Extenders for long-range missions.</li> <li>French Rafale fighters rely on C-135FR tankers for extended deployments.</li> <li>RAAF F/A-18F Super Hornets use KC-30A tankers for maritime patrols.</li> <li>Israeli F-35I Adir fighters benefit from Boeing 707-based Re'em tankers.</li> <li>US Navy uses KC-46 Pegasus tankers for fast refueling of F/A-18E/F Super Hornets.</li> </ul> <p>Despite its advantages, the flying boom system may not be optimal for refueling multiple lightweight fighters when compared to the probe-and-drogue system.</p> | [19–21] |

drogue method. Lee et al. [22] Investigated the stereo vision pipeline and validated to perform pose estimation for AAR with a novel ground experiment. A novel drogue measurement method using a monocular vision for autonomous aerial refueling task in unmanned aerial vehicles (UAV) was proposed [23]. The study involves an arc-level drogue detection and recognition algorithm and secondly, a pose estimation algorithm which were validated based on the real air refueling task data set, ground acquisition data, and simulation experiments.

### In-flight refueling of helicopter

Aerial refueling competency is crucial for the Warfare search and rescue operations since it prominently outspreads the operating range of the helicopter and thus allows the operational

unit to extend their rescue capabilities over larger battle space. Air Force rescue missions which often takes place in the harshest and most challenging environments, highlights the essential need to use AAR [24]. Military and civilian helicopters are refuelled in-flight using the probe and drogue method. This capability enables the helicopters to reach extremes of the operating country's territory, includes the rescue missions carried out at sea levels, humanitarian aid, troop infiltrations and military transport at strategic co-ordinates [2]. Evaluation of real-time simulation environment for helicopter air-to-air refueling (HAAR) investigations were reported by Schmidt et al. [25]. The importance of HAAR and the progress made in constructing a simulation scenario for HAAR in a research environment were discussed. The author results indicate that maintaining a position relative to the tanker





Figure 4. In-flight refueling of fighter

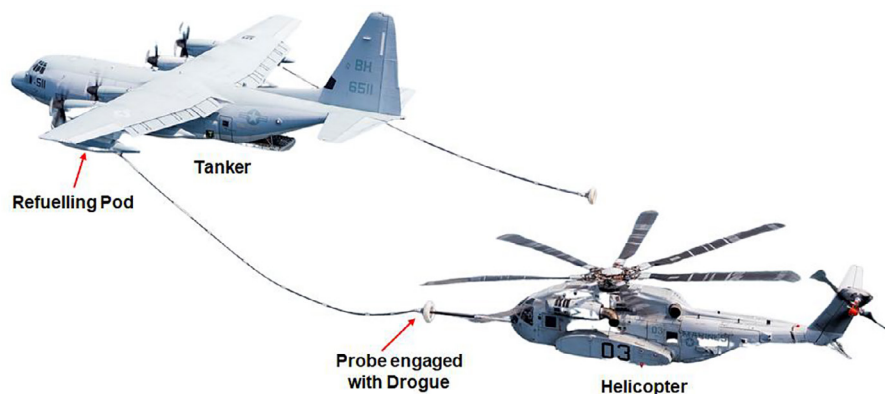


Figure 5. In-flight refueling of helicopter [24]

is challenging. The methods and techniques developed for the HAAR qualification process between the helicopter H225M and the tanker KC-130H was by presented brazilian flight test and research institute (IPEV) [26]. To prevent rotor-hose entanglement, helicopter probes are designed longer, as illustrated in Figure 5.

### Buddy refueling

Buddy refueling is an in-flight fuel transfer technique between two combat aircraft, designed to support tactical military operations without relying on dedicated tankers. Modern fighter jets are equipped with this capability using an external “buddy pod” mounted on a hard point, containing a hose-and-drogue refueling system [5, 8]. Although the fuel transfer capacity is limited – typically between 1500 kg to 2000 kg – it provides operational flexibility, especially for naval fighter aircraft operating from carriers. Originally developed for deck-based aircraft, buddy refueling allows fighters to take off with heavier payloads and refuel mid-air. It also enables aircraft to be reconfigured as temporary tankers. As shown in Figure 6, a fighter performing a buddy refueling

role can act either as a mission tanker – accompanying strike aircraft to top up fuel mid-route – or as a recovery tanker – stationed above the carrier to assist returning aircraft with low fuel, enhancing safety during landings. This method extends strike ranges and mitigates fuel emergencies during carrier operations. Bloy et al. [27] developed a static hose-drogue model for simulation using the finite element method, applying constant drag to represent flight conditions. Kaushik et al. [28] addressed pilot visibility challenges during aerial refueling in poor visibility and night conditions by developing a drogue detection system based on an opto-mechanical model, improving accuracy and situational awareness during refueling. Conventional aerial tankers face limitations due to their large size, which reduces manoeuvrability and agility, especially in contested airspace. In contrast, buddy refueling systems offer greater flexibility and can operate effectively in hostile environments. This capability enhances a fighter’s combat radius and loiter time without relying on dedicated tankers. Modern fighter jets equipped with buddy refueling systems include the Rafale, Su-30MKI, F/A-18 Super Hornet, MiG-29K/M, Shenyang J-15, and Tornado.



Figure 6. Fighter in buddy refueling role

### Combination of refueling methods through boom drogue adapter

Military planners have a problem when it comes to mixed forces because the flying boom equipment is incompatible with the probe-and-drogue system. These concerns can be addressed through converting a flying boom system to a PDRS using a special adapter unit known as boom drogue adapter (BDA) unit [5, 8]. Tanker aircraft with this special adapter configuration retain their articulated boom, but the end of the hose has a drogue instead of the normal nozzle. The adapter unit uses a steel basket instead of the soft canvas basket used in drogue systems. The soft traditional Drogues accepts refueling contact even though probe of the receiver is not well in axis, while the metal drogue, when contacted even slightly off centre, will hinge out of place, thus damaging the fuselage. Details of tanker with BDA and fighter refueling through BDA are illustrated in Figure 7. Although a boom can have a drogue adapter attached, this still commits the tanker to one aircraft at a time and one type of system per flight. The

boom drogue adapter conversion will not support in-flight refueling of helicopters. Tankers KB50, KC97, KC-135 of US Airforce and Tanker KC-135FR of French Air Force also uses the special adapter unit BDA equipped with refueling boom which extends the ability to connect with the probe and drogue system.

Another major advantage of this system is that the hose does not retract into an HDU during in-flight engagement between probe and drogue. As the hose is pushed towards the boom, it bends in response to how far it is being pushed. Over-extending it can cause the boom to engage with the rigid boom, damage the windscreen, or loop around the probe. Insufficient pressure will cause the probe to disengage, which will prevent the aircraft by halting the refueling process. Staying connected to a KC-135 adapter unit is much harder to do than it is to stay connected in a traditional probe-drogue configuration because of a much smaller tolerance to keep up its position during flight. The receiver aircraft begins to decelerate after the fuelling process is finished until the

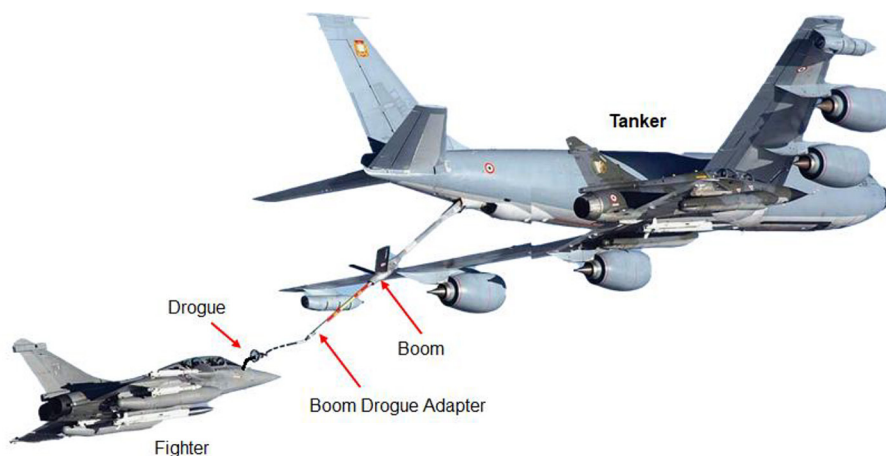


Figure 7. Tanker with BDA

probe nozzle separates from the Drogue's coupling. As similar to engagements scenarios, off-centre disengagements also have the potential to send the Drogue "crashing" into the Probe or into the aircraft's fuselage. McRoberts et al. [29] worked on the tanker wake and rollup conditions using a line vortex model for a flight in non-uniform wind. The authors achieved acceptable amount of accuracy the single-point model in all regions of the tanker wake, except close to the tanker wake downstream of the wing tip vortex.

### Multiple systems

Some tankers come equipped with a Boom as well as one, two, or more hose and drogue systems. These system are referred to as the multiple-point refueling system, or MPRS, if they are mounted to the wings [30]. Figure 8 depicts a visual representation of the multiple point refueling system. The probe-drogue system is situated at the aircraft's tail, whereas the Boom is positioned at the centre line of the aircraft. On using these types of systems only one equipment may be used simultaneously. But with such a system, all varieties of aircraft with probe and receptacle equipment can be refuelled in a single flight without having to land and set up an adapter. The US Air Force KC-10, Airbus A330 MRTT, and MPRS KC-135 all have distinct hose and drogue systems in addition to flying booms. Doebbler et al. [31] worked on the autonomous operation of a non-micro sized UAV using a vision sensor based active deformable contour algorithm and the integration of navigation system with the boom controller.

### Wing to wing system

This approach, which involves the tanker aircraft deploying a flexible hose from its wingtip, is comparable to the probe and drogue approach but more complex. The receiver uses a unique lock under its wingtip to catch the hose while flying behind it. The fuel supply is pumped to the receiving aircraft from the supply aircraft once the hose is connected and secured. A pictorial representation of wing-to-wing refueling method is shown in Figure 9. Wing to wing refueling method was developed by Russian test pilots and subsequently adopted by the Soviet Air force and used through the late 1990s, but no other country utilised this method, believing it to be too risky. A detailed comparison and respective classifications of probe and drogue refueling systems are provided in Table 3.

This section discussed the diverse applications of the Probe-and-Drogue system in aerial refueling operations. Fighter and helicopter refueling highlight the method's role in extending range and mission endurance, though helicopter refueling poses additional challenges due to rotor wash and positional stability. Buddy refueling offers tactical flexibility for carrier-based aircraft but is constrained by limited fuel capacity. Adaptations such as the boom-drogue adapter and multiple-point refueling systems enhance interoperability by supporting both boom and probe-equipped aircraft within a single operation. The rarely used Wing-to-Wing method, though innovative, was deemed impractical due to safety risks. Collectively, these approaches underscore the operational versatility of the Probe-and-Drogue system, while also emphasizing its technical and logistical trade-offs across different mission profiles.

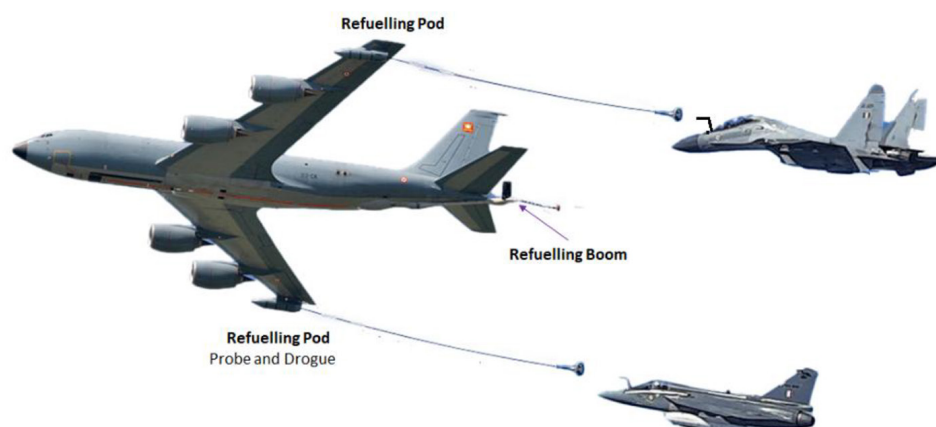


Figure 8. Tanker with MPRS



**Table 3.** Classification and detailed comparison of probe and drogue refueling system

| Process                                | Advantages                                                                                                                                                                        | Disadvantages                                                                                                                                                              | Ref            |
|----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| Fighter refueling                      | <ul style="list-style-type: none"> <li>Extends range and operational flexibility</li> <li>Allows for hot-air refueling (without landing)</li> </ul>                               | <ul style="list-style-type: none"> <li>Requires specialized tanker aircraft and pilot training</li> </ul>                                                                  | [32]           |
| Helicopter refueling                   | <ul style="list-style-type: none"> <li>Extends mission time for helicopters</li> <li>Allows for refueling in remote locations</li> </ul>                                          | <ul style="list-style-type: none"> <li>Requires specialized training for helicopter pilots</li> <li>More susceptible to turbulence due to helicopter rotor wash</li> </ul> | [3], [33]–[35] |
| Buddy refueling                        | <ul style="list-style-type: none"> <li>Offers flexibility in situations where dedicated tanker support is unavailable.</li> <li>Used for short-range extensions.</li> </ul>       | <ul style="list-style-type: none"> <li>Requires precise coordination between pilots.</li> <li>Limited fuel transfer capability compared to dedicated tankers.</li> </ul>   | [6], [36]      |
| Boom-drogue adapter (BDA)              | <ul style="list-style-type: none"> <li>Offers flexibility for tankers to refuel both boom and probe equipped aircraft</li> <li>Reduces need for separate tanker fleets</li> </ul> | <ul style="list-style-type: none"> <li>Adds complexity to tanker operations</li> <li>Potential performance limitations compared to dedicated drogue systems</li> </ul>     | [37], [38]     |
| Multiple-point refueling system (MPRS) | <ul style="list-style-type: none"> <li>Significantly increases refueling efficiency</li> <li>Ideal for large formations of fighters or bombers</li> </ul>                         | <ul style="list-style-type: none"> <li>Requires specialized tanker aircraft and complex coordination - High initial investment and maintenance costs</li> </ul>            | [39], [40]     |
| Wing-to-wing refueling                 | <ul style="list-style-type: none"> <li>Simple and utilizes low-tech components</li> <li>No specialized equipment required</li> </ul>                                              | <ul style="list-style-type: none"> <li>Extremely dangerous due to risk of collision - Inefficient and slow refueling rate</li> </ul>                                       | [41]           |



**Figure 9.** Wing-to-wing refueling

## TYPES OF REFUELING PROBES

Aerial refueling probes are classified into fixed and retractable probes based on their construction and operation. The retractable probe is further categorized into a telescopic, actuated and articulated probe. An aircraft design house selects an appropriate type of refueling probe for implementation based on design feasibility and performance. Probe design is evolved with apt geometrical dimensions, to achieve the requests such as pilot vision, aerodynamic performance, dissipation of structural attachment loads, probe and drogue clearance envelope and inboard feasibility. The performance

and handling characteristics of a receiving aircraft may be impacted by the aerodynamic effects of the Probe across the flight envelope. Hence, the refueling probe type must be appropriately selected. Fixed probe is chosen, where the nose section of the aircraft is small and it houses essential electronic warfare equipment and sensors like infrared search and track system (IRST), Radar, etc., On the other hand a Retractable Probe is chosen to achieve reduction in drag, enhanced performance and stealth and of course there is adequate volume to accommodate it when retracted into the front fuselage [15]. This following section describes the modern state of the art and provides references for those

interested in the classification of refueling probes. The various types of AAR probes are described and reference is made to the overall configuration of their refueling systems. The installation and operations of these systems and their sub-systems is discussed in some detail.

### Fixed refueling probe

A fixed refueling probe is installed in the front section of the aircraft, ensuring that it is aerodynamically shaped to reduce the drag. Fixed probe is chosen in order to reduce complexity and therefore avoid deployment/retraction problems. Combat aircraft integrated with a fixed refueling probe is shown in Figure 10. Schmelz et al. [42] worked on the design and assessment of fighter pilot assistance systems for AAR using probe-to-drogue-equipment. The fixed refueling probe is configured with structural rigidity to withstand aerodynamic stresses, and loads encountered during refueling operation. The fixed probe is designed considering both fitted and removed configurations. Details of a typical fixed refueling Probe are given in Figure 11.

The fixed probe is designed using the modular construction concept for ease of installation, removal, maintenance and overhaul. A typical fixed aerial refueling probe assembly consists of 4 sub-assemblies viz., nozzle, weak link, mast and spigot. The function of a nozzle is to interface with the refueling drogue coupling. The weak link assembly functions like a mechanical fuse and protects the aircraft structure in the event of exceedance of radial load which is likely to occur during the coupling with the drogue. The MAST facilitates fuel transfer and transfer's hose

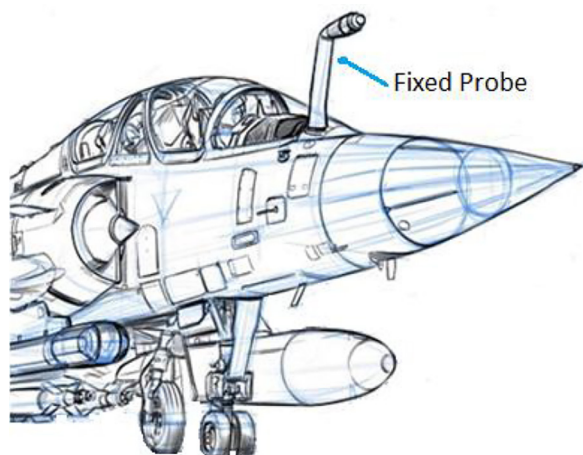


Figure 10. Aircraft with fixed refueling probe

load from Nozzle to mounting attachment. It is aerodynamically shaped. Spigot sub-assembly is to support the sealing between probe and aircraft mounting bracket. Bhandari et al. [43] studied the bow wave effects and emphasized a possible solution for successful autonomous operations in AAR. The offset method which was applied was found to recover most of the performance loss due to the bow wave effect in the probe and the drogue AAR refueling simulation.

### Retractable refueling probe

High performance Stealth aircraft with an internal weapon bay are incorporated with a retractable refueling probe in order to reduce aerodynamic drag and radar cross-section. Stealth capability is attained through hiding the refueling probe under the fuselage after the completion of in-flight refueling operation. Retractable probes are designed considering the requirements of both extended and retracted configurations. Picture of aircraft with retractable refueling probe is shown in Figure 12.

Electrical, hydraulic, or pneumatic mechanisms could be used to extend and retract the telescoping probes. The actuation approach will operate throughout the range of refueling envelope. If the primary actuation technique does not work, an emergency method for activating the probe is also provided. For the purpose of indicating whether the device is extended or retracted, the system is equipped with proximity sensors [44]. While an excessively slow actuation can affect the refueling time, an excessively fast actuation can result in excessive forces within the actuation system. Therefore, the actuation period for the probe is between the ranges of 5 to 20 seconds.

Here, the classification of aerial refueling probes into fixed and retractable designs reflects a balance between aerodynamic efficiency,

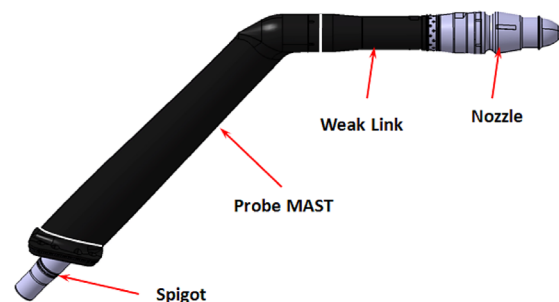
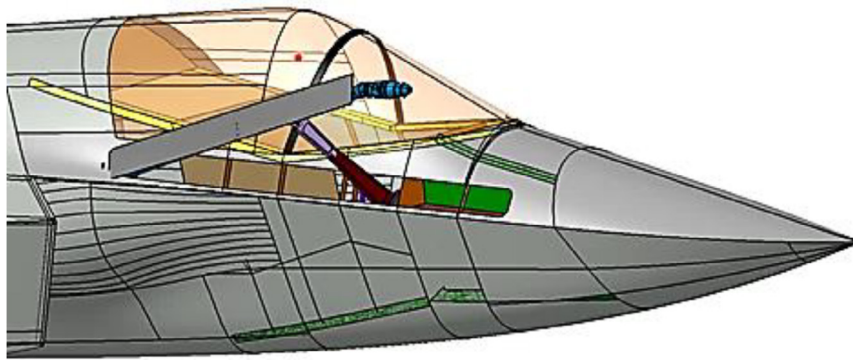


Figure 11. Details of fixed refueling probe [13]



**Figure 12.** Aircraft with retractable refueling probe

structural integration, and stealth considerations. Fixed probes, often used in aircraft with limited fuselage space, prioritize simplicity and reliability but impose permanent aerodynamic effects. In contrast, retractable probes, widely employed in modern stealth platforms, minimize drag and radar signature while introducing greater mechanical complexity through actuation systems. Collectively, these probe types highlight the design trade-offs between operational performance, structural feasibility, and mission-specific requirements.

## CLASSIFICATION OF RETRACTABLE PROBES

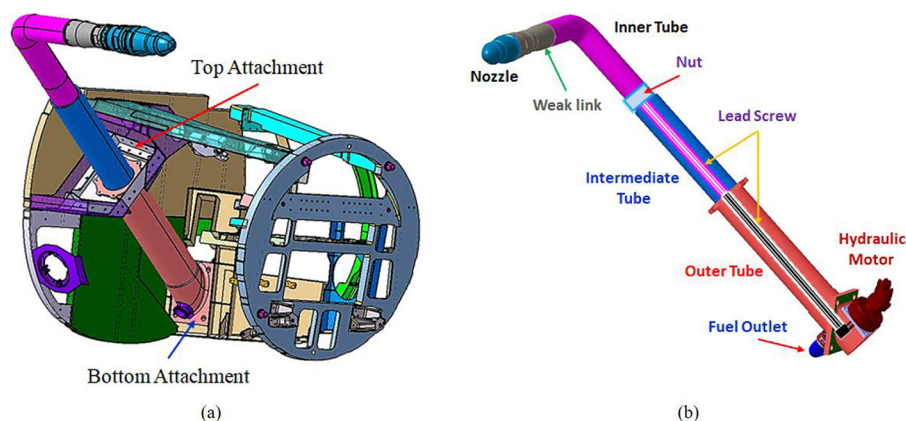
Design of a retractable refueling probes system is a compromise between many conflicting requirements such as space availability, number of elements, actuation mechanism, kinematics, etc. Based on the constructional features and technique of operation, retractable refueling probes are classified into telescopic, actuated and articulated types. Designers choose between these types based on design feasibility studies. Details

of retractable refueling probes are brought out in the following section.

### Telescopic refueling probe

Telescopic refueling probe is chosen where there is a space constraint in the aircraft inboards in the longitudinal direction. The telescope refueling probe is configured with a base tube and series of collapsible tubes for achieving a long stroke length. Telescoping describes the movement of one telescopic tube sliding out from another thus lengthening the refueling probe from its stowed position to the desired extended condition. Telescoping is commonly restricted to a maximum of 6 stages for better stability. Cross section of a combat aircraft's front fuselage integrated with a telescopic refueling probe is depicted in Figure 13a.

Details of a telescopic refueling probe assembly proposed to be used in the Indian Medium Weight Fighter Aircraft (MWFA) are presented in Figure 13b. It is formed by three telescoping tubes (Inner, Intermediate and Outer) which are actuate-able for extension and retraction. The outer



**Figure 13.** Telescopic refueling probe (a) complete installation scheme and (b) schematic representation

tube is static and intermediate & inner tube will be sliding. An electric or hydraulic motor is used to move the telescoping members between the extended and retracted positions. The telescoping members are entirely contained inside the aircraft when they are in retracted state. The Probe nozzle attached to the innermost tube stretches out to the suitable point in its extended position, allowing the pilot to view it clearly from the cockpit. In order to keep the motor away from the fuel zone, it is mounted in the dry compartment.

An extended jack or lead screw that engages a fastener component that is directly attached to the innermost tube during the extension operation which converts the motor's rotational drive to a linear drive, causing the innermost tube to move linearly as the motor rotates. Another jack screw or a slide-able drive is used to linearly drive the additional extendable telescoping tubes, of which there may be one, two, or more, in response to the motor's rotational drive. Thus, with the help of this technique, where reversing the motor's rotation causes the telescoping tubes to retract into the fuselage while also reversing their linear motion. Telescopic tubes are appropriately designed to support various loads experienced during refueling operation (especially at full extension, they are subjected to large side forces). The side forces are addressed through sufficient bearing area (overlapping of intermediate tube with outer tube and inner tube with intermediate tube). Typically, the collapsed length of a base or outer tube is around 20 to 40% of the fully extended length depending on the number of stages.

## Actuated refueling probe

Actuated refueling probe (retractable type) is used where there is a space constraint in the lateral and vertical direction of a front fuselage. The refueling probe is extended and retracted using appropriate linear or rotary hydraulic actuator. The electro-hydraulic actuator is preferably used for compactness of equipment and to attain automatic control. A combat aircraft integrated with actuated refueling probe is shown in Figure 14.

The main refueling probe assembly consists of refueling boom, nozzle, weak link, and spherical attachment joint. The refueling boom is built-in with bracket and spherical joint for enabling structural integration. Also, it has provision for fixed door fitment and eye end bracket for the attachment of foldable/collapsible actuating link. The bracket will be attached to the aircraft structure using tension bolts. Bolted joint is designed to dissipate refueling and carriage loads to the aircraft structure. The Spherical joint will ensure frictionless angular rotation or movement during probe extension and retraction. Foldable link (upper and lower) is attached to the refueling boom through bolted joint and further the lower link is attached to linear hydraulic actuator. A typical actuated refueling probe proposed for a twin engine stealth fighter is shown in Figure 15.

The extension and retraction of refueling probe is achieved through hydraulic means. The actuation method will be functional throughout the refueling envelope. An emergency method to actuate the probe is also provided in the event

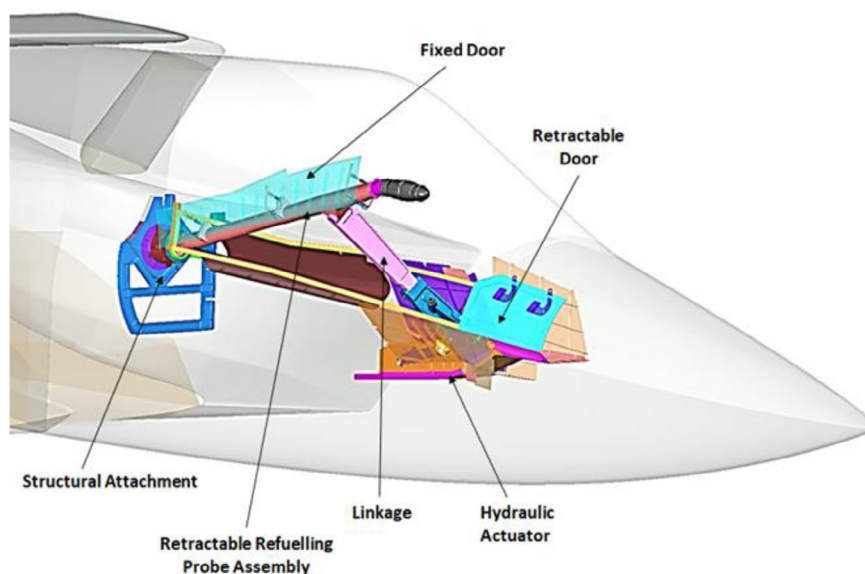


Figure 14. Fighter with actuated refueling probe



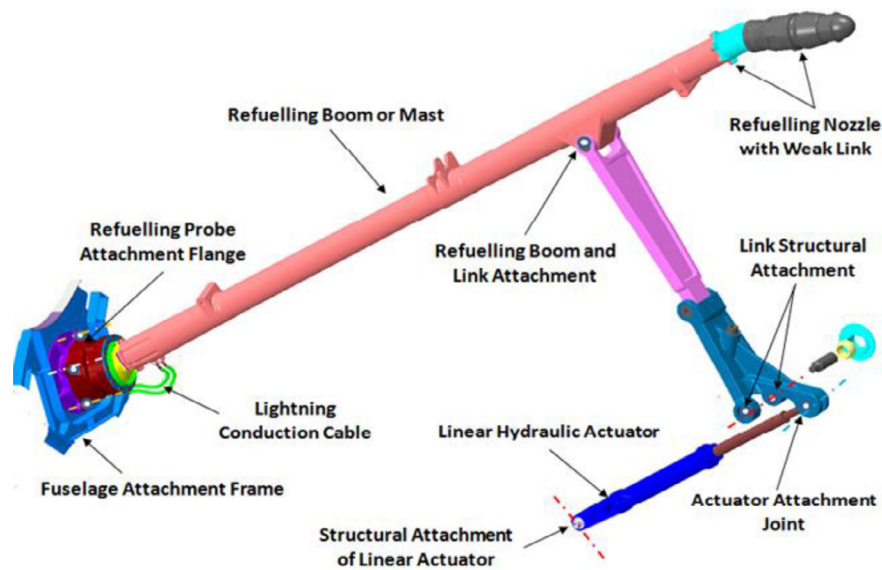


Figure 15. Details of actuated refueling probe

the primary actuation method fails. The system is provisioned with proximity sensors for indicating the status of extended or retracted position. An actuation which is too rapid can cause excessive forces within the actuation mechanism, while an actuation time that is too long can impact the refueling time. Thus, the Probe actuation time is optimised between 10 to 20 Seconds. During the deployment of refueling probe, the solenoid operated selector valve would supply pressurised hydraulic fluid to the extension port of hydraulic actuator. The actuator will convert the supplied hydraulic energy into mechanical force. This mechanical force will be utilized to attain the physical movement of fork link (lower link) and then fork link will further actuates the collapsible link to the fully extended condition ensuring that the refueling Probe reaches the

desired position. An appropriate restrictor will be incorporated in the hydraulic circuit to control the rate of extension and retraction. On selection of switch to retract position, the solenoid selector valve will supply pressurised fluid to the retract port of the actuator, causing the link assemblies to collapse which further results in the retraction of refueling probe assembly within the aircraft inboards.

### Articulated refueling probe

Refueling probe with articulation mechanism is implemented where compactness is required for accommodating the refueling probe assembly. An articulated joint is a spherical joint with an angular drive. Fighter aircraft integrated with articulated refueling probe system is shown in Figure 16. An



Figure 16. Fighter jet equipped with articulated probe

articulated refueling probe system is constructed and arranged for extension to a preferred position wherein the refueling probe is rigidly extended and articulated to a folded position within the aircraft. The articulated mechanism contains angular actuation and linear motion. Angular actuation is achieved through linear or rotary actuator and linear motion through telescopic tube mechanism. As detailed in Figure 17, the articulated probe possesses specific characteristics that contribute to its functionality. During extension operation, the refueling probe assembly will be angularly actuated by electro-hydraulic actuator through actuating arm. Further, linear extension of probe tip to the desired coordinates is attained by telescopic stroke. Articulation function of the Probe assembly is achieved by means of spherical end fitting. Retraction of refueling probe assembly is attained by pull back of hydraulic actuator, which will then collapse the actuating arm and telescopic tubes resulting in stow back of Probe assembly into the aircraft inboards.

In summary, retractable refueling probes can be broadly classified into telescopic, actuated, and articulated types, each tailored to specific spatial constraints within the aircraft fuselage. Telescopic probes use concentric tubes to maximize reach where longitudinal space is limited, while actuated probes employ a simple pivoting mechanism to address lateral or vertical constraints. Articulated probes combine angular rotation with telescopic extension, offering the most compact storage solution for aircraft with stringent internal space restrictions. The selection of a probe design thus represents a balance between storage efficiency, mechanical complexity, and operational requirements.

### Evolution and advancements in drogue systems

The concept of aerial refueling emerged in the early 20th century. Initial attempts involved rudimentary techniques like transferring fuel between buckets or hoses dangled from one aircraft to another. The development of the drogue system in the mid-20th century marked a significant advancement. Early drogues were constructed from canvas or fabric, offering a stable and forgiving target for probe insertion. The drogue system serves as a critical component of the hose-and-drogue aerial refueling method. It is a funnel-shaped device suspended from a flexible hose deployed by the tanker aircraft. The receiving aircraft manoeuvres its refueling probe into the

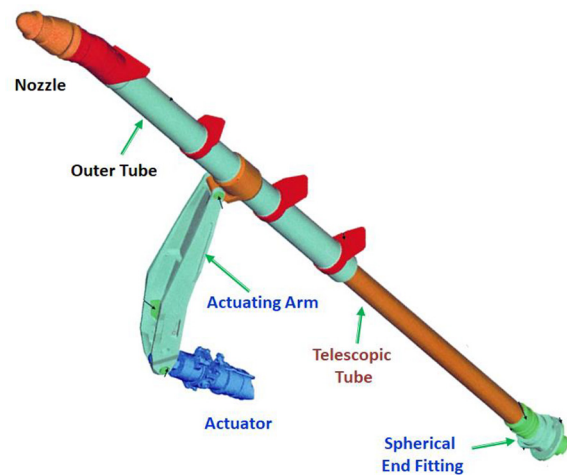


Figure 17. Particulars of articulated probe

drogue basket to establish a secure connection for fuel transfer. The design of the drogue system directly impacts the efficiency, stability, and safety of aerial refueling operations [45, 46].

### Types of drogue systems

Drogue systems are not a one-size-fits-all solution. Their design and functionality are tailored to the specific needs of the aerial refueling operation. Here, we explore two key classifications and delve deeper into the variations that exist within these categories.

#### Classification based on vehicle operation

Drogue systems are specialized devices used in aerial refueling operations to guide the refueling probe of a receiving aircraft into the hose of a tanker aircraft. These systems can be classified primarily based on the operational context of the aerial refueling vehicle, distinguishing between military and commercial applications [47]. Military drogue systems are engineered to meet the rigorous demands of high-speed, high-altitude refueling operations. These systems are optimized for stability and robustness under dynamic conditions. Stability is paramount in military applications to ensure successful probe insertion despite turbulence and the high relative speeds of the aircraft. To achieve this, military drogues often have larger diameters, providing a more substantial target area for the receiving aircraft. Additionally, they may incorporate advanced stabilizing mechanisms such as aerodynamic vanes, fins, or strakes that help to maintain a steady position in the airflow. These design elements are crucial

in ensuring that the drogue remains stable and aligned, reducing the risk of damage to both the drogue and the probe during the refueling process. Research highlights the importance of stability in military drogue systems. For instance, studies have shown that larger drogue diameters and enhanced stabilization techniques significantly improve the success rates of aerial refueling operations under adverse conditions [48]. Furthermore, military drogues are often constructed from durable materials to withstand the harsh operational environments and the mechanical stresses encountered during frequent use.

In contrast, commercial drogue systems are designed for refueling procedures that generally occur at lower speeds and altitudes compared to their military counterparts. The primary focus in commercial applications is on efficiency and weight reduction. Commercial drogues are typically lighter and may not require the same level of aerodynamic stabilization as military systems. This is because commercial aerial refueling operations are often conducted in more controlled environments where extreme turbulence and high-speed manoeuvres are less common. Efficiency in commercial drogue systems is achieved through streamlined designs that minimize drag and weight. This is essential for commercial operations where fuel efficiency and operational costs are critical considerations. Moreover, commercial drogues might incorporate materials and design features that prioritize ease of maintenance and longevity, ensuring that they remain functional over extended periods with minimal servicing requirements [49].

#### *Variations in design and functionality*

Drogue systems exhibit a wide range of designs and functionalities beyond their basic classification by vehicle operation. These variations are driven by the need to enhance stability, facilitate probe insertion, and ensure reliable operation under various conditions.

One common approach to stabilizing drogue systems involves the use of passive aerodynamic features such as vanes, fins, or strakes. These components help to counteract the aerodynamic forces acting on the drogue, maintaining its position and orientation relative to the airflow. Passive stabilization is particularly effective in maintaining a steady position without the need for complex control mechanisms. Research indicates that passive stabilization techniques can significantly reduce the oscillations and positional deviations

of drogues, thereby improving the ease and reliability of probe insertion [50].

Some drogue systems incorporate inflatable elements that expand the drogue basket, providing a larger target area for the receiving aircraft's probe. This design innovation addresses the challenge of precise alignment between the probe and drogue, especially under conditions where the receiving aircraft may have limited manoeuvrability. Inflatable drogues can be deployed rapidly and offer the advantage of being compact and lightweight when not in use, contributing to overall efficiency and ease of storage [4].

Advanced drogue systems may feature control mechanisms that allow for precise positioning by the tanker crew. These systems are particularly relevant for large refueling tankers or operations conducted in challenging weather conditions. Control mechanisms can include servo motors or actuators that adjust the position and orientation of the drogue based on real-time feedback from sensors. This level of control enhances the accuracy of the refueling process and reduces the likelihood of failed engagements or damage to the equipment [51], [52]. These variations in design and functionality highlight the ongoing development of drogue systems. As aerial refueling technology continues to evolve, we can expect to see even more innovative approaches to drogue design that enhance stability, efficiency, and safety across all applications.

#### *Drogue stabilisation and enhanced controllability*

The development of drogue stabilization and control represents a significant leap forward in AAR technology. This advancement promises to enhance safety, efficiency, and operational flexibility, allowing air forces to project power more effectively in complex scenarios. As research continues, these systems have the potential to become even more robust and widely adopted, ushering in a new era of reliable and adaptable air-to-air refueling [53].

#### *Aerodynamic forces and stability challenges*

During flight, the drogue system is subject to a variety of aerodynamic forces that can impact its stability and performance. These forces include drag, flutter, and turbulence, which are influenced by the air flowing past the drogue and hose. Drag acts as a resistive force that can slow down the drogue and affect its alignment. Flutter, which involves oscillations caused by aerodynamic forces,

can lead to instability and potential structural failure. Turbulence, characterized by chaotic and irregular air movements, further complicates the stability of the drogue [54]. The interaction of these forces can create significant challenges for maintaining a stable drogue during aerial refueling operations. If the drogue becomes unstable, it can result in difficulty for the receiving aircraft to connect securely, increasing the risk of mid-air collisions or unsuccessful refueling attempts. Ensuring the drogue's stability is therefore critical for the safety and efficiency of these operations. Research in this area highlights the importance of understanding the complex aerodynamic interactions and developing solutions to mitigate their impact [55].

### *Mechanisms for drogue stabilization*

To address the stability challenges posed by aerodynamic forces, various mechanisms have been developed to stabilize the drogue system. One such mechanism involves the use of fixed or deployable vanes. These vanes can be strategically positioned on the drogue to generate counteracting forces that help maintain a stable orientation. By adjusting the angle and position of the vanes, it is possible to counteract destabilizing forces such as drag and flutter, thereby enhancing the overall stability of the drogue [56]. Another effective stabilization mechanism is the incorporation of inflatable devices within the drogue. These devices can be inflated to increase the drogue's diameter, which helps to dampen the effects of wind gusts and turbulence. By increasing the surface area and mass of the drogue, inflatable devices provide additional stability, reducing the likelihood of oscillations and erratic movements. The use of these stabilization mechanisms has been shown to significantly improve the success rate and safety of aerial refueling operations, as they enable the drogue to maintain a more consistent and predictable position [51].

### *Control systems for precise positioning*

In addition to passive stabilization mechanisms, advanced drogue systems may also incorporate active control systems to achieve precise positioning [57, 58]. These control systems allow the tanker crew to make real-time adjustments to the drogue's position, which is particularly beneficial for large refueling tankers where the drogue is deployed at a considerable distance from the aircraft. By using control systems, the crew can

compensate for environmental factors such as wind shear or turbulence, ensuring a smoother and more efficient refueling process [59]. Control systems typically involve a combination of sensors, actuators, and feedback mechanisms that enable precise manipulation of the drogue's position. For instance, sensors can detect changes in the drogue's orientation or external forces acting upon it, while actuators can make the necessary adjustments to maintain the desired position. Feedback mechanisms provide real-time data to the crew, allowing them to monitor and control the drogue with high accuracy. The implementation of such control systems has been shown to enhance the reliability and safety of aerial refueling operations, making it easier for the receiving aircraft to establish and maintain a secure connection [60]. This section has delved into the drogue system as a pivotal element in aerial refueling vehicles, providing a comprehensive exploration of its development, classification, design variations, and aerodynamic considerations. Over the years, drogue technologies have advanced from simple connection mechanisms to highly engineered systems shaped by innovations in materials, computational modelling, and control techniques. These improvements have enhanced stability, durability, and reliability in demanding combat conditions. In summary, the future of drogue systems is expected to be driven by the integration of advanced materials and intelligent automation, enabling safer operations, improved resilience against adverse flight environments, and compatibility with the performance requirements of next-generation manned and unmanned aircraft. Table 4 outlines the major milestones, current practices, and future trends that are anticipated to influence drogue technology in aerial refueling.

### **Standard modelling of refueling systems**

Typical air-to-air refueling procedure and equipment's for the use of tanker and receiver aircraft have been standardized and described by NATO. In the standard model, refueling is divided into ten phases from 0 to 9 to simplify the modelling process [75] as mentioned below. The aerial refueling sequence begins with the drogue positioned inside the pod or hose drum unit (HDU). Following this, the drogue is deployed outward into the airflow. Once fully extended, it trails behind the tanker and becomes clearly visible, allowing the receiver aircraft to align and make contact with the drogue. Initially, contact



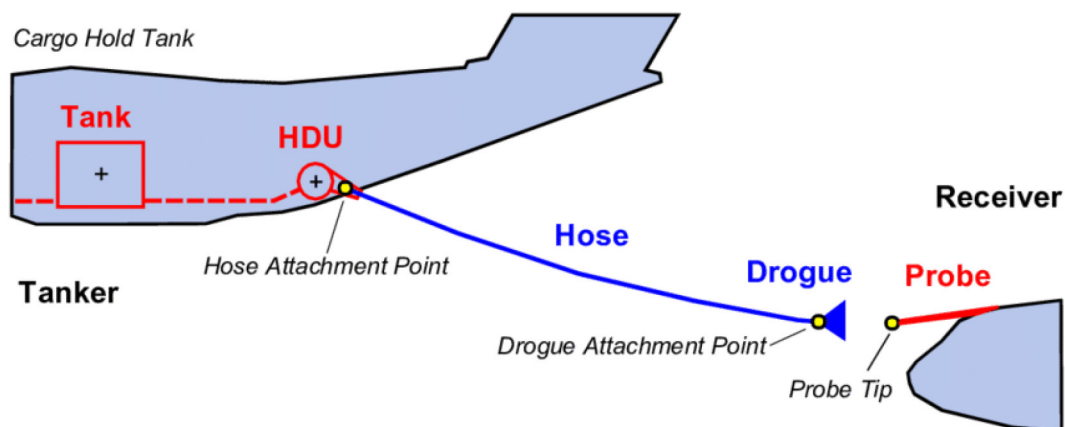
**Table 4.** Highlights of findings and future trends for development in drogue systems

| Section                        | Research focus                                | Inference                                                                                                                                                                | Ref      |
|--------------------------------|-----------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| Summary of findings            | Historical development of drogue systems      | The evolution of drogue systems in aerial refueling vehicles has been comprehensively explored, highlighting key historical milestones.                                  | [15, 61] |
|                                | Classification and design variations          | Drogue systems have been classified based on various operational needs, showing different designs and functional variations.                                             | [62]     |
|                                | Aerodynamic challenges and stability          | Identified the aerodynamic challenges affecting drogue stability and discussed mechanisms to enhance controllability.                                                    | [63, 64] |
| Future trends and developments | Advancements in materials                     | The future of drogue systems involves using lightweight and self-healing composite materials to improve performance.                                                     | [41, 65] |
|                                | Integration of advanced control systems       | Advanced control systems with real-time feedback are expected to enable more precise drogue positioning and automation.                                                  | [66, 67] |
|                                | Advantages of enhanced drogue controllability | Enhanced drogue controllability can improve safety by reducing connection failures, speed up refueling, enable AAR in challenging weather, and facilitate UAV refueling. | [68–70]  |
|                                | Challenges with active control systems        | Active control systems add complexity, increase costs, and require regular maintenance to ensure optimal performance.                                                    | [71, 72] |
|                                | Implications for AAR technology               | Developments in drogue stabilization and control represent significant advancements in AAR technology, enhancing safety, efficiency, and operational flexibility.        | [73, 74] |

may occur outside the refueling zone, where no fuel transfer takes place. As the probe enters the refueling zone, fuel flow commences, continuing even as the aircraft moves into the stand-off zone. Once the receiver reaches the cut-off zone, fuel transfer stops. After refueling is completed, the probe is disconnected from the drogue, and the two aircraft are safely separated. Finally, the drogue is retracted back into the HDU, marking the end of the refueling operation. Fuel can be transferred either directly from the tanker's own fuel compartments or from additional cargo hold tanks. Cargo hold tanks are always preferred in this type of models, as they function as a buffer between the tanker and receiver. The system configuration details are shown in Figure 18.

## AUTONOMOUS FLIGHT CONTROL SYSTEM

The autonomous aerial refueling system requires explicit knowledge to function properly. The flight system must be aware of the positions of all the markers in order to recognize the tanker's exact location coordinates [76]. However, a narrow imbalance between the nominal design position and the real marker position if seen will lead to the deformation of tanker frame. A pictorial depiction of autonomous aerial refueling process using Probe and Drogue method is shown in Figure 19. The advanced sensors considered in automated AAR flights are designed in preferred circumstances such that it is able to


**Figure 18.** AAR system configuration with a probe and drogue model [50]



**Figure 19.** AAR system configuration with a probe and drogue model

sense the relative position of tanker, receiver and refueling hardware, both for the safer execution of engage/disengage operations. It is essential for any equipment to be able to track and dock with a moving drogue in turbulent conditions on considering precise measurements at a rapid rate to suitably capture the drogue's dynamic behaviour. Several technologies are available to enable these capabilities, including, machine vision, satellite navigation and radar applications.

The design for autonomous flight control systems (AFCS) in aerial refueling includes the selection of sensors which are capable of detecting the relative position between the tanker aircraft and the receiver aircraft, as well as to establish control laws that can guide the process during aerial refueling. Using image-based inspection to identify objects in UAS operations has become increasingly popular. Aerial refueling, navigation, tracking, collision avoidance, and automatic landing have all been investigated with vision sensors. An interpretation of these aircrafts relative position and the respective orientation can be made available, when a global coordinate frame is known within which the camera would be located to detect and identify key information about the target [50, 77–79].

On considering the autonomous operations involved in AAR such as uniformed flying formations and air refueling, both the extended vision range and proximity measurements are required at different phases of aerial operations. In order to achieve these unmanned operations in AAR, extensive researches are carried on differential

global positioning system (DGPS), formation flight instrumentation systems (FFIS), multi-model adaptive extended kalman filter (MM EKF) and VisNav an active vision-based sensor developed at the Texas A&M University [80–83].

As a standard technology, DGPS meets the demands in wide range of relative navigation applications. In general, GPS satellite signals are corrected utilizing these reference stations on the ground via DGPS. The accuracy is usually greater than that of GPS, with position errors typically ranging from one to three meters [84]. The accessibility of providing proper vision intensity at the connecting drogue area were studied [28], such that the receiver aircraft identifies the location of drogue from a desired distance and its angle of connection with the probe. Valasek et al. [85] recommended the use of an optical sensor which could be fixed on the tanker aircraft and detect the drogue location for its respective connection with probe system in AAR. Several LED based beacons are attached to the drogue. Analysis of signals sent between the beacons and the optical sensor leads to the determination of the six degree-of-freedom sensor position and attitude data with respect to a reference frame fixed on the drogue. Campa et al. [86] demonstrated a simulation environment for the autonomous docking of probe and drogue system using a fuzzy fusion method to determine the drogue's position considering the GPS and machine vision based information. Using the boom and receptacle method, authors worked on designing autonomous aerial refueling systems which employed fuzzy fusion

strategy. Markers were placed on the tanker aircraft to determine the aircraft's relative position with respect to the unmanned aerial vehicle (UAV) with a machine vision system. A linearized model is used to describe UAV dynamics in the study. Table 5 summarizes the advantages and disadvantages of AAR in autonomous applications based on the sensors and instruments discussed here.

## FLIGHT TEST

The usage of in-flight large-scale airframes and refueling equipment's are expensive and showcases a volume of risks involved. Despite the costly considerations, these testing methods can be an effective future method of research, and is certainly a necessary step in taking any AAR solution to production. Military operations have become more dependent on CAVs. These vehicles are able to operate more effectively with autonomous aerial refueling in a variety of ways. A number of challenges exist in the autonomous aerial refueling of CAVs [12, 88]:

1. Accurate positioning of tankers based on their relative positions. Combat vehicles are required to operate close to tanker aircraft during refueling procedures. It is therefore imperative for the receiver aircraft to know exactly where it is with regard to the tanker aircraft:
2. Collision avoidance – during aerial refueling, it is vital for the receiver vehicle to avoid colliding with the tanker aircraft.
3. Command and control – in the event of an unsafe refueling condition, CAVs need to respond to the boom operator's breakaway commands.
4. Constraints imposed by real-world conditions – in all weather conditions and at any time of the day or night, the AAR must be functional.

Burns et al. [89] worked on investigating the Flight tests and Man-in-the-loop simulation stations which were helpful in understanding the potential problems of combat aircrafts autonomous AAR. Williams et al. [90] developed a prototype UAV control station interface for automated refueling planes as part of the man-in-the-loop framework. During the air refueling phase of flight, it is employed to manage a number of unmanned aircraft. The interface performed satisfactorily on consecutive validation tests though several issues are still to be addressed. In addition to the simulations on the man-in-the-loop system, flight testing has been used to verify the concept and possibility of automated aerial refueling of UAVs [91]. The processes of developing an in-house dynamic hose and drogue system model was studied and supported by NASA Dryden flight research centre for the enhancement of AAR experimental testing capabilities and its implementation in actual combat conditions [45].

## THE FUTURE OF AIR-TO-AIR REFUELING

Air-to-air refueling has made it possible to extend the operational range of military aircraft since the mid-twentieth century. Initially, the refueling techniques were impractical and risky, even though they aimed to reduce inter-continental freight transport costs. The critical analysis of available refueling methods reveals that the Probe and Drogue Method stands out as a highly suitable option for combat applications. This method offers flexibility and precision, making it easier to establish a connection between the tanker and receiver aircraft during in-flight refueling [15]. The flying boom method, while efficient for certain scenarios, can be

**Table 5.** Summary of navigation systems for autonomous aerial refueling

| Autonomous navigation systems | Advantages                                                                                             | Disadvantages                                                                          | Ref  |
|-------------------------------|--------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------|
| Differential GPS              | Sensor measurements are applicable in long range requirements                                          | Low frequency refresh rate and accuracy, reliability issues, and prone to jamming.     | [80] |
| Vision based sensors          | High frequency refresh rate and accuracy, less power requirement, and reduced size and weight.         | Exposed to more line collision scenario, More sensitive towards visibility conditions. | [81] |
| FFIS                          | Moderate frequency refresh rate and well established commercially available hardware.                  | Less accuracy, line colloidal and reliability issues.                                  | [87] |
| MM EKF                        | Enhanced frequency refresh rate and accuracy in autonomous operations and robust to equipment failure. | Prone to line pileup issues and not flight tested yet.                                 | [82] |

less versatile and adaptable, potentially limiting its application in combat situations [4]. The wing-to-wing system lacks the agility and adaptability that the probe and drogue method offers. Fixed probes are robust and reliable but may create additional aerodynamic drag when not in use. Retractable probes offer the advantage of reducing drag when not in use, contributing to improved aircraft performance, but they come with added complexity in terms of maintenance and operational reliability.

Despite these advantages, the use of AAR systems in combat conditions introduces several limitations and risks. Tanker aircraft, due to their larger size and predictable flight paths, are often considered high-value targets and may be vulnerable to enemy interception or long-range missile threats. The operational environment further amplifies challenges, as wake turbulence, wind gusts, and limited visibility complicate precise hose and drogue alignment. In hostile airspace, these aerodynamic difficulties are compounded by potential electronic warfare tactics such as jamming or communication interference, which can disrupt navigation and coordination during refueling manoeuvres [92, 93]. Another operational risk lies in the inherent requirement for close-proximity flying between multiple aircraft. Under high-threat conditions, pilots face increased cognitive load, as they must balance situational awareness, threat detection, and the precision of the refueling process. The predictable orbit patterns used during refueling can also expose both tanker and receiver aircraft to enemy surveillance and targeting, thereby limiting the tactical flexibility of combat missions. From a technical perspective, differences in refueling systems across allied forces may restrict interoperability in joint operations. Also, integration with existing platforms poses challenges, as variations in compatibility, fuel transfer efficiency, and environmental adaptability can restrict deployment. Adverse weather conditions, turbulence, and limited visibility in contested airspaces further reduce operational reliability.

In terms of tactical risks, reliance on autonomous or semi-autonomous operations may raise concerns related to decision-making in unpredictable combat scenarios. Delays in response time, system errors, or unanticipated behaviour could have significant consequences

in high-stakes missions. Besides, autonomous flight control systems are increasingly integrated to enhance safety and precision, their reliance on advanced software introduces new risks related to reliability, cyber threats, and potential system malfunctions in combat environments [52]. The integration of AAR systems into combat operations also faces substantial logistical and economic challenges. Although advancements in design and manufacturing have reduced unit costs over time, the overall expense of procurement, deployment, and long-term maintenance remains considerable. Combat-ready AAR platforms require continuous technical support, routine servicing, and timely replacement of components, all of which add to operational expenditures. Moreover, sustaining such systems in remote or hostile environments demands a robust supply chain capable of providing spare parts, specialized repair facilities, and trained personnel, which may not always be feasible during extended combat missions.

The future needs of air-to-air refueling will largely be shaped by the number of potential receiver aircraft and their operating ranges. While the probe and drogue method remains widely adopted by most air forces and navies due to its operational advantages, it is clear that limitations such as tanker vulnerability, aerodynamic instability, interoperability challenges, and electronic warfare threats must be addressed. As technology advances, continued improvements in these systems are expected to enhance efficiency and reliability, while also ensuring resilience under the demanding conditions of modern combat. Looking ahead, future research should focus on the integration of autonomous aerial refueling with unmanned combat systems. The increasing reliance on UAVs, ranging from small reconnaissance drones to advanced unmanned combat air vehicle, makes the ability to conduct mid-air refueling without human pilots a critical enabler for extended endurance and operational reach. Research is required to develop robust refueling interfaces specifically designed for UAVs, as current systems are optimized primarily for manned aircraft. This includes the design of lightweight, aerodynamically efficient refueling probes and drogue systems that minimize drag and energy consumption while ensuring compatibility across diverse UAV platforms.



## CONCLUSIONS

The review demonstrated the significant growth of air-to-air refueling system in combat aircrafts. The design specifications for fighter aircraft demands the increase in operation capabilities, airborne persistence, and longer-range strike platforms for specific combat operational needs. Several aspects to in-flight refueling processes were reviewed and discussed in this paper, including refueling methods, the merits and demerits of each type of refueling probe, and the classification of retractable refueling probes. These aspects will provide an insight to aircraft design houses in choosing appropriate combat technology for AAR systems based on trade-off studies, design feasibility and operational necessity. The use of various refueling systems, particularly the probe-and-drogue system, is crucial for extending the range and operational capabilities of military aircraft. This study emphasized the importance of these systems and the critical role of experimental standard testing in advanced AAR technology. Testing ensures the development of reliable and efficient refueling systems by mitigating risks and uncertainties and remains indispensable for certification and validation.

The probe-and-drogue system is a versatile and widely adopted AAR method that can be adapted to specific operational requirements. The future work in the advancement of combat aerial vehicle refueling systems includes the development and implementation of cutting-edge technologies and strategies aimed at enhancing the efficiency, reliability, and safety of in-flight refueling operations. Future advancements are expected to focus on autonomous refueling systems, advanced fuel transfer mechanisms, and the integration of real-time monitoring with predictive data analytics to ensure optimal performance and safety. Additionally, the adoption of sustainable and alternative fueling solutions will play a vital role in addressing environmental concerns. The incorporation of virtual simulation-based training platforms will contribute to improved pilot readiness and operational efficiency.

## Acknowledgement

The authors would like to thank and acknowledge all the works carried out by eminent authors referred in this article.

## REFERENCES

1. Macgregor P., In-Flight Refuelling, *Aircr. Eng. Aerosp. Technol.*, Dec. 1961, 33(12), 362–363, <https://doi.org/10.1108/eb033495>
2. Smith R. K., *Seventy-Five Years of Inflight Refueling*, 1st ed. Air Force History and Museums Program, 1998.
3. Fezans N. and Jann T., Modeling and Simulation for the Automation of Aerial Refueling of Military Transport Aircraft with the Probe-and-Drogue System, Jun. 2017. <https://doi.org/10.2514/6.2017-4008>
4. Bolkcom C., *Air Force Aerial Refueling Methods : Flying Boom versus Hose-and-Drogue*, 2006. [Online]. Available: <https://apps.dtic.mil/sti/citations/ADA454450>
5. Killingsworth P., *Multipoint aerial refueling a review and assessment*. RAND Corporation, 1996.
6. Theiss B. J., *A Comparison of In-flight Refuelling methods for Fighter Aircraft: Boom-receptacle vs. Probe-and-Drogue*, Embry-Riddle Aeronaut. Univ., 2007.
7. Office of the Secretary of Defense, *Unmanned Aircraft Systems Roadmap, 2005–2030*, 2005.
8. Vicenz U., *Aerial Refueling -the First Century: History, Methods, Airplanes and Operators*. Company of Lulu Press, 2019.
9. An S. and Yuan S., Relative position control design of receiver UAV in flying-boom aerial refueling phase, *ISA Trans.*, Feb. 2018, 73, 40–53, <https://doi.org/10.1016/j.isatra.2017.12.006>
10. Ferwerda D. et al., *Aerial Refueling Probe/Drogue System*, 2018. <https://apps.dtic.mil/sti/citations/AD1064517>
11. Arumugam A. et al., Innovative method for the estimation of closure velocity between RAT driven drogue and IFR probe air to air refueling flight trials, *Def. Sci. J.*, Mar. 2020, 70(2), 140–144, <https://doi.org/10.14429/dsj.70.14100>
12. Mao W. and Eke F. O., A survey of the dynamics and control of aircraft during aerial refueling, *Nonlinear Dyn. Syst. Theory*, 2008; 8(4), 375–388.
13. Prasad V. K., Design and development of air to air refuelling capability for Tejas aircraft and flight testing, *Technol. Spectr.*, 2020.
14. Cobham Mission Equipment, *Buddy Refuelling System*, 2014.
15. Purdy S. I., Probe and drogue aerial refueling systems, *Encycl. Aerosp. Eng.*, 2010, <https://doi.org/10.1002/9780470686652.eae580>
16. Patton S., An analysis of the value of air-to-air refuelling to modern air operations, *Air Sp. Power Rev.*, 2019, 23(1), 1–23,
17. Dutta A. N., To fill a critical gap, Indian Air Force looks to buy six mid-air refuellers, 2018. [Online].

- Available: <https://indianexpress.com/article/india/to-fill-a-critical-gap-iaf-looks-to-buy-six-mid-air-refuellers-8915461/>
18. Cobb M. R., *Aerial Refueling: The Need for a Multi-point, Dual-System Capability*, Air Univ. Press, 1987.
19. Weidemann T., How aerial refueling works for military aircraft, 2023. [Online]. Available: <https://aeroreport.de/en/good-to-know/how-aerial-refueling-works-for-military-aircraft>
20. Bolkcom J. D., Christopher & Klaus, *Air Force Aerial Refueling Methods: Flying Boom versus Hose-and-Drogue*, Washington D.C., 2005. <https://digital.library.unt.edu/ark:/67531/metacrs6702/>.
21. States U. and Accountability G., KC-46 TANKER MODERNIZATION Program Cost Is Stable, but Schedule May Be Further Delayed Report to Congressional Requesters United States Government Accountability Office, no. April, 2018.
22. Lee A., Dallmann W., Nykl S., Taylor C., and Borghetti B., Long-range pose estimation for aerial refueling approaches using deep neural networks, *J. Aerosp. Inf. Syst.*, Nov. 2020, 17(11), 634–646, <https://doi.org/10.2514/1.1010842>
23. Ma Y., Zhao R., Liu E., Zhang Z., and Yan K., A novel autonomous aerial refueling drogue detection and pose estimation method based on monocular vision, *Measurement*, Mar. 2019, 136, 132–142 <https://doi.org/10.1016/j.measurement.2018.12.060>
24. Lockheed M., Combat rescue helicopter programme successfully executes major test milestone: Aerial refuelling, *Vector Star Newsletter*, 2021.
25. Schmidt S. O., Jones M., and Löchert P., Evaluation of a real-time simulation environment for helicopter air-to-air refuelling investigations, *Aeronaut. J.*, May 2023, 127(1311), 754–772, <https://doi.org/10.1017/aer.2022.106>
26. de Paula L. G. L., de Freitas A. C., Figueira J. M. P., da Silva R. G., and Cruz R. V., Development of new flight test techniques for helicopter air to air refueling qualification process, Jan. 2022. <https://doi.org/10.2514/6.2022-0198>
27. Bloy A. W. and Khan M. M., Modeling of the receiver aircraft in air-to-air refueling, *J. Aircr.*, Mar. 2001, 38(2), 393–396, <https://doi.org/10.2514/2.2775>
28. Kaushik N., Garg H., Meena A., and Mali H. S., Materials and design for drogue detection in air-to-air refueling, *Mater. Today Proc.*, 2021, 44, 4503–4508, <https://doi.org/10.1016/j.matpr.2020.10.727>
29. McRoberts R., Early J. M., Price M. A., Morscheck F., Li M., and La Rocca G., Improving feasibility of point to point operations through civil aerial refueling, Jun. 2014. <https://doi.org/10.2514/6.2014-3272>
30. Holder B. and Holder W. G., *Range Unlimited: A History of Aerial Refueling*. Schiffer Publishing, 2000.
31. Doebller J., Spaeth T., Valasek J., Monda M. J., and Schaub H., Boom and Receptacle Autonomous Air <https://doi.org/10.2514/1.28305>
32. Maurer M. and United States. Air Force. Office of Air Force History., *Air Force combat units of World War II*. 1983.
33. Kalt D. H., Tipton R., Martin L., Ferwereda D., Benson D. A., and Ezfa A., *ARSAG Aerial Refueling Probe / Drogue System*, 2018.
34. Yakovlieva A. V., Boichenko S. V., and Zaremba J., Improvement of air transport environmental safety by implementing alternative jet fuels, in *2019 Modern Safety Technologies in Transportation (MOSATT)*, Nov. 2019, 146–151. <https://doi.org/10.1109/MOSATT48908.2019.8944122>
35. Shapland J. S., Probe and drogue aerial refueling requirements : How will air force special operations command meet future demands ? By a thesis presented to the faculty of the school of advanced airpower studies for completion of graduation requirements school of advance, no. June, 2002.
36. Liu H. et al., Modelling the quasi-static flexural behaviour of composite sandwich structures with uniform- and graded-density foam cores, *Eng. Fract. Mech.*, 2022, December 2020, 259, 1–18, <https://doi.org/10.1016/j.engfractmech.2021.108121>
37. Yost K. A. and Washburn A. R., Optimizing assignment of air-to-ground assets and BDA sensors, *Mil. Oper. Res.*, Mar. 2000, 5(2), 77–91, <https://doi.org/10.5711/morj.5.2.77>
38. Kopp C., *Laser Remote Sensing - A New Tool for Air Warfare*, 2010, 1–19.
39. Liberman E. J., *Air force institute of technology*, no. March, 2015.
40. Parry J. and Hubbard S., Review of sensor technology to support automated air-to-air refueling of a probe configured uncrewed aircraft, *Sensors (Basel)*, 2023, 23, <https://doi.org/10.3390/s23020995>
41. Fernandes G. and Maldonado V., The U.S. air force next-generation air-refueling system: A resurgence of the blended wing body?, *Aerospace*, Jun. 2024, 11(6), 494, <https://doi.org/10.3390/aerospace11060494>
42. Schmelz J., Lachmann J., Ament J., and Wandrey L. S., Design and assessment of fighter pilot assistance systems for air-to-air refuelling with probe-to-drogue-equipment, 2022.
43. Bhandari U., Thomas P. R., and Richardson T. S., Bow wave effect in probe and drogue aerial refuelling, Aug. 2013. <https://doi.org/10.2514/6.2013-4695>
44. Samuelsson J., A study into relative navigation methods for automatic probe and drogue air-to-air refuelling, 2020.
45. Hansen J., Murray J., and Campos N., *The NASA Dryden AAR Project: A Flight Test Approach to an*

- Aerial Refueling System, Aug. 2004. <https://doi.org/10.2514/6.2004-4939>
46. Mati R., Pollini L., Lunghi A., Innocenti M., and Campa G., Vision-Based Autonomous Probe and Drogue Aerial Refueling, in 2006 14th Mediterranean Conference on Control and Automation, Jun. 2006, 1–6. <https://doi.org/10.1109/MED.2006.328794>
47. Chen S., Duan H., Deng Y., and Li C., Drogue pose estimation for unmanned aerial vehicle autonomous aerial refueling system based on infrared vision sensor, *Opt. Eng.*, Dec. 2017, 56(12), 1, <https://doi.org/10.1117/1.OE.56.12.124105>
48. Gao Y., Yang S., and Liu X., Drogue position measurement of autonomous aerial refueling based on embedded system, *Sensors Actuators A Phys.*, 2023, <https://doi.org/10.1016/j.sna.2023.114251>
49. Kochersberger K., Modeling of Probe-and-Drogue Part of an Master of Science Jeffrey Kozak Edward Hensel, 2004.
50. Fezans N. and Jann T., Towards automation of aerial refuelling manoeuvres with the probe-and-drogue system: modelling and simulation, *Transp. Res. Procedia*, 2018, 29, 116–134, <https://doi.org/10.1016/j.trpro.2018.02.011>
51. Williamson W. R., Reed E., Glenn G. J., Stecko S. M., Musgrave J., and Takacs J. M., Controllable Drogue for Automated Aerial Refueling, *J. Aircr.*, Mar. 2010, 47(2), 515–527, <https://doi.org/10.2514/1.44758>
52. Dibley R., Allen M., and Nabaa N., autonomous airborne refueling demonstration phase i flight-test results, Aug. 2007. <https://doi.org/10.2514/6.2007-6639>
53. Yuan D. et al., Study on the controllability of a drogue for hose-drogue aerial refueling system, in 2017 11th Asian Control Conference (ASCC), Dec. 2017, 2592–2595. <https://doi.org/10.1109/ASCC.2017.8287584>
54. Sun Y., Liu Z., Zou Y., and He X., Active disturbance rejection controllers optimized via adaptive granularity learning distributed pigeon-inspired optimization for autonomous aerial refueling hose-drogue system, *Aerosp. Sci. Technol.*, 2022, 124, 107528, <https://doi.org/10.1016/j.ast.2022.107528>
55. Kuk T. and Ro K., Design, test and evaluation of an actively stabilised drogue refuelling system, *Aeronaut. J.*, Nov. 2013, 117(1197), 1103–1118, <https://doi.org/10.1017/S0001924000008721>
56. Ren J. and Quan Q., Progress in modeling and control of probe-and-drogue autonomous aerial refueling, *Chinese J. Aeronaut.*, Nov. 2023, <https://doi.org/10.1016/j.cja.2023.11.011>
57. Chen X. and Tomizuka M., Control methodologies for precision positioning systems, in 2013 American Control Conference, Jun. 2013, 3704–3711. <https://doi.org/10.1109/ACC.2013.6580403>
58. Uzunovic T., Golubovic E., Kebude D., and Sabanovic A., Control system for high precision positioning applications based on piezo motors, in 2015 IEEE International Conference on Mechatronics (ICM), Mar. 2015, 116–121. <https://doi.org/10.1109/ICMECH.2015.7083958>
59. ARSAG, Automated Aerial Refueling Concept of Operations, 2020.
60. Kriel S. C., Engelbrecht J. A. A., and Jones T., Receptacle normal position control for automated aerial refueling, *Aerosp. Sci. Technol.*, 2013, 29(1), 296–304, <https://doi.org/10.1016/j.ast.2013.03.011>
61. Nangia R. K., Operations and aircraft design towards greener civil aviation using air-to-air refuelling, *Aeronaut. J.*, 2006, 110(1113), 705–721, <https://doi.org/10.1017/S0001924000001585>
62. La Rocca G., Li M., Van Der Linden P. P. M., and Elmendorp R. J. M., Conceptual design of a passenger aircraft for aerial refueling operations, 29th Congr. Int. Counc. Aeronaut. Sci. ICAS 2014, 2014.
63. Zhou W. et al., Aerodynamic characteristics analysis of refueling drogue under the influence of bow wave effect based on patched grid technology, 2022, 803–813. [https://doi.org/10.1007/978-981-16-7423-5\\_80](https://doi.org/10.1007/978-981-16-7423-5_80)
64. Salehi Paniagua K., García-Fogeda P., and Arévalo F., Aeroelastic Stability of an Aerial Refueling Hose–Drogue System with Aerodynamic Grid Fins, *Aerospace*, May 2023, 10(5), 481, <https://doi.org/10.3390/aerospace10050481>
65. Zhang Z., Huang Z., Liu X., and Feng B., Research on multiple air-to-air refueling planning based on multi-dimensional improved NSGA-II algorithm, *Electronics*, Sep. 2023, 12(18), 3880, <https://doi.org/10.3390/electronics12183880>
66. Lampl T. S., Integrated Design of Advanced Flight Control Configurations and System Architectures, 2021.
67. Thomas P. R., Bhandari U., Bullock S., Richardson T. S., and du Bois J. L., Advances in air to air refuelling, *Prog. Aerosp. Sci.*, Nov. 2014, 71, 14–35, <https://doi.org/10.1016/j.paerosci.2014.07.001>
68. Ren J., Quan Q., Liu C., and Cai K., Docking control for probe-drogue refueling: An additive-state-decomposition-based output feedback iterative learning control method, *Chinese J. Aeronaut.*, 2020, 33, 1016–1025, <https://doi.org/10.1016/j.cja.2019.11.007>
69. Liu Z., Liang J., Zhao Z., Efe M. O., and Hong K. S., Adaptive fault-tolerant control of a probe-and-drogue refueling hose under varying length and constrained output, *IEEE Trans. Control Syst. Technol.*, 2022, 30(2), 869–876, <https://doi.org/10.1109/TCST.2021.3079275>



70. Wu L., Sun Y., Zhao K., and Fu X., A novel vision-based PRPL multistage image processing algorithm for autonomous aerial refueling, *Wirel. Commun. Mob. Comput.*, vol. null, p. null, 2021, <https://doi.org/10.1155/2021/2778857>
71. Ro K., Kuk T., and Kamman J., Active control of aerial refueling hose-drogue systems, Aug. 2010. <https://doi.org/10.2514/6.2010-8400>
72. Fravolini M. L., Ficola A., Campa G., Napolitano M. R., and Seanor B., Modeling and control issues for autonomous aerial refueling for UAVs using a probe-drogue refueling system, *Aerosp. Sci. Technol.*, Oct. 2004, 8(7), 611–618, <https://doi.org/10.1016/j.ast.2004.06.006>
73. Keiser N. L., A systematic review of technology in the after-action review (or debrief), *Organ. Psychol. Rev.*, Apr. 2024, <https://doi.org/10.1177/20413866241245314>
74. Bitoun A., Innovative analysis tools for after action review ( AAR ) using ai and modeling & simulation, in *Towards Training and Decision Support for Complex Multi-Domain Operation*, 2021, 1–16.
75. NATO Standardization Agency, *Air-to-Air Refueling*, 2013.
76. Hanson C., Ryan J., Allen M., and Jacobson S., An overview of flight test results for a formation flight autopilot, Aug. 2002. <https://doi.org/10.2514/6.2002-4755>
77. Wu A. D., Johnson E. N., and Proctor A. A., Vision-aided inertial navigation for flight control, *J. Aerosp. Comput. Information, Commun.*, Sep. 2005, 2(9), 348–360, <https://doi.org/10.2514/1.16038>
78. Conte G. and Doherty P., Vision-based unmanned aerial vehicle navigation using geo-referenced information, *EURASIP J. Adv. Signal Process.*, Dec. 2009, 2009(1), 387308, <https://doi.org/10.1155/2009/387308>
79. Campoy P. et al., Computer vision onboard UAVs for Civilian Tasks, *J. Intell. Robot Syst.*, 2009, 105–135, [https://doi.org/10.1007/978-1-4020-9137-7\\_8](https://doi.org/10.1007/978-1-4020-9137-7_8)
80. Kaplan Elliott D., Hegarty Christopher J., *Understanding GPS : principles and applications*, 2nd Editio. Artech House, 2006.
81. Luo D., Shao J., Xu Y., and Zhang J., Docking navigation method for UAV autonomous aerial refueling, *Sci. China Inf. Sci.*, Jan. 2019, 62(1), 10203, <https://doi.org/10.1007/s11432-018-9578-9>
82. Awalt B., Turner D., Miller R., and Chen W.-Z., Extended kalman filter applications to multi-vehicle UAV cooperative controls, Sep. 2003. <https://doi.org/10.2514/6.2003-6538>
83. Williamson W. et al., An instrumentation system applied to formation flight, May 2002. <https://doi.org/10.2514/6.2002-3430>
84. United States, *Coast Guard Navigation Standards Manual*, 2020.
85. Valasek J., Gunnam K., Kimmet J., Tandale M. D., Junkins J. L., and Hughes D., Vision-based sensor and navigation system for autonomous air refueling, *J. Guid. Control. Dyn.*, Sep. 2005, 28(5), 979–989, <https://doi.org/10.2514/1.11934>
86. Campa G., Fravolini M. L., Ficola A., Napolitano M., Seanor B., and Perhinschi M., Autonomous aerial refueling for UAVs using a combined GPS-machine vision guidance, Aug. 2004. <https://doi.org/10.2514/6.2004-5350>
87. Junkins J. L., Hughes D. C., Wazni K. P., and Pariyapong V., Vision-based navigation for rendezvous, docking and proximity operations, *Adv. Astronaut. Sci.*, 1999, 101, 203–220.
88. Nalepka J. and Hinchman J., Automated Aerial Refueling: Extending the Effectiveness of UAVs, Aug. 2005. <https://doi.org/10.2514/6.2005-6005>
89. Burns R., Clark C., and Ewart R., The automated aerial refueling simulation at the AVTAS Laboratory, Aug. 2005. <https://doi.org/10.2514/6.2005-6008>
90. Williams R., Feitshans G., and Rowe A., A Prototype UAV control station interface for automated aerial refueling, Aug. 2005. <https://doi.org/10.2514/6.2005-6009>
91. Nguyen B. and Lin T., The use of flight simulation and flight testing in the automated aerial refueling program, Aug. 2005. <https://doi.org/10.2514/6.2005-6007>
92. Liu Y., Wang H., and Fan J., Novel docking controller for autonomous aerial refueling with probe direct control and learning-based preview method, *Aerosp. Sci. Technol.*, Nov. 2019, 94, 105403, <https://doi.org/10.1016/j.ast.2019.105403>
93. Dogan A., Sato S., and Blake W., Flight control and simulation for aerial refueling, Aug. 2005. <https://doi.org/10.2514/6.2005-6264>