An Emulation of a Flying Boom Operator Using a Rule-Based Expert System

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ABSTRACT

Aerial refueling consists of transferring fuel from one aircraft to another during flight. Currently, the U.S. military employs two main aerial refueling technologies: the flying boom and the probe-and-drogue systems. Both Air-to-Air Refueling (AAR) techniques are complex and require significant training. AAR training can be conducted using flight simulators because they provide several advantages, including a safe training environment and a significant reduction in the cost of training. However, to conduct effective Virtual Aerial Refueling (VAR) training, the simulators must be designed to satisfy several elements of fidelity. Normally, VAR training is conducted using a synthetic environment with the capability of generating constructive entities that perform the role of either aircraft tanker or aircraft receiver. When the simulator is used as the receiver aircraft, a constructive aircraft is simulated to be used as the tanker, or vice-versa. However, the utilization of a constructive aircraft tanker equipped with a flying boom refueling system will be limited if there is a lack of realism of the flying boom movement during the pre-contact and disconnect phases. Consequently, this type of training does not provide the required fidelity for a high level of training transfer.

To enhance the realism and consequently maximize the training transfer of VAR training with a flying boom refueling system, this study uses an Artificial Intelligence (AI) approach to emulate the actions and procedures that flying boom operators would perform during AAR missions. To do so, KC-135 boom operator experts were interviewed to gather their expert knowledge, and then a rule-based expert system was developed that emulates the action of a boom operator. This paper will present the algorithm to emulate the action of a boom operator, the results of its implementation to a KC-135 constructive tanker, the validation of the algorithm, and the crucial lessons learned from this effort.

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INTRODUCTION

The United States Air Force (USAF) Distributed Mission Operations (DMO) concept is one of the most successful applications of modeling and simulation for distributed training. DMO is a USAF initiative that enables warfighters to train and maintain combat readiness by conducting mission rehearsal in a synthetic environment that is realistic. The ability of the USAF to achieve training and mission rehearsal objectives is well established in the DMO program. The distributed mission-training concept was designed to achieve these training objectives. It introduced high-fidelity training devices and the capability for them to link with training devices connected to the same network.

The DMO Concept of Operations (CONOPS) objectives are specifically addressed in the USAF DMO implementation plan (USAF Distributed Mission Operations CONOPS White Paper, 20 October 2003). The DMO plan is subdivided into the following five air and space objectives (USAF Distributed Mission Operations Implementation Plan, 15 November 2004**)** to replicate and integrate:

- Command and Control (C2) capabilities, including the Tactical Air Control System
- Intelligence, Surveillance, and Reconnaissance (ISR) and reconnaissance capabilities
- USAF force application capabilities
- USAF force projection capabilities
- Homeland Defense (HLD) capabilities

Aerial Refueling capability is defined in the "Replicate and integrate USAF force projection capabilities" objective and represents an effective method of increasing the range of aircraft. It consists of transferring fuel from one aircraft to another during flight. The additional fuel transferred to the aircraft receiver will be used during the same flight and enable the receiver aircraft to remain airborne longer.

Currently, the U.S. military employs two main Air-to-Air Refueling (AAR) technologies: flying boom and probe-and-drogue (P&D). The first method of AAR uses a flying boom, which is a gimballed, telescopic probe that is "flown" by a boom operator in coordination with the pilot in order to insert into the refueling receptacle on the receiving aircraft. The boom is retractable when not in use. The second method of AAR uses a trailing hose with the basket on the end. The P&D system is more complex than the flying boom system. It consists of three disparate dynamics parts: the probe, the drogue, and the hose drum. Both AAR techniques are complex and require significant training. When the P&D method is used, the receiving aircraft pilot must guide the probe of their aircraft into the basket to connect with the hose of the tanker. For the flying boom refueling system, the boom operator of the aircraft tanker must guide the boom to the receptacle of the receiver aircraft.

The purpose of using a flight simulator as the receiver aircraft is to train the student pilot to perform the following:

- Familiarity with AAR procedure to achieve close visual contact between receiver and tanker (i.e., rendezvous [RV] procedure, which could be established with just a single or a formation of tankers)
- Receiver position prior and during refueling operation
- Receiver sequence during refueling operation
- Boom signal and tanker Pilot Director Lights (PDLs)
- Post refueling and reform

This paper uses an Artificial Intelligence (AI) approach to emulate the actions of a flying boom operator of a constructive tanker. To do so, we interviewed a boom operator to gather expert knowledge and then simulated this knowledge using a rule-based expert system technique. The simulation of a boom operator was implemented to a simulation of a KC-135 synthetic tanker. The simulation results demonstrated that by using the rule-based expert system technique, the simulation could realistically reproduce the movement of the flying boom as it was controlled by a boom operator.

BACKGROUND

Air-to-air refueling training transfer from aircraft to simulator

AAR operations require significant training to ensure effectiveness and safety. A tanker such as KC-135 burns over 4000 lbs. of fuel per hour. Flying a 4-hour sortie burns approximately 16,000 pounds of fuel. An aerial refueling mission also requires an extensive support package in order to complete the mission. From ground crews to personnel who service, maintain, and marshal the aircraft, all add cost to the aerial refueling training. Distributed VAR training saves millions in flying hour costs per year. This training capability enabled the USAF to reduce flying hours by shifting the aerial refueling training to simulators (Carretta & Dunlap, 1998). Therefore, the possibility to train VAR over a DMO network represents a significant cost benefit because virtual refueling training not only saves money but also requires far less support than live training.

Training transfer represents the process from which the knowledge and skills acquired through the training are applied to the real situation (Allen, Hays, & Buffardi, 2001; Noble, 2002). The fidelity of the equipment used for the training and environment from which the training is performed are closely linked to training transfer. Therefore, poor fidelity usually leads to negative training transfer. For VAR, training is usually conducted using flight simulators because they provide several advantages, including a safe training environment and a significant reduction in the cost of training. The fidelity of a flight simulator consists of three fundamental elements: physical, cognitive, and operational. Physical fidelity refers to the level to which the simulator replicates the real aircraft cockpit. Physical fidelity includes visual, sound, and motion (Allen et al, 1986). Cognitive fidelity represents the ability of a simulator to reproduce a training environment that replicates the cognitive skills required in the cockpit (Lee, 2009). Lastly, the operational fidelity represents the level at which the simulator can replicate the real cockpit (Allen et al., 1986). To conduct effective VAR training, simulators must be designed to satisfy all three elements of fidelity.

To conduct effective VAR training, simulators must be designed to satisfy all three elements of fidelity. One approach to ensure a positive training transfer of VAR training would be to connect simulators to a local network. This provides a higher fidelity of training as simulators are controlled by humans rather than computers. While this training approach is effective, it presents some limitations. The interoperability between simulator participants in the same training exercise is possible via a private software interface. The use of a private interface presents a critical issue because each company manufactures their simulators using their own private interface, rendering them incompatible to interface with each other and, therefore, preventing them from participating in the same training scenario. To accomplish VAR over a network, both the tanker and receiver aircraft require a common interface so they can interoperate. Furthermore, all of the required data needs to be on the network to support visually seeing the aircraft and their articulations, feeling the wakefield, and, most importantly, transferring the fuel. While networks today do have an increased capacity to transmit and receive communication data, multiple training exercises passing all of the data at 60 Hz can easily bog down the system, especially if simulators are located at different sites. Data needs to be organized in a manner that enables the simulator to render the other simulators correctly and interact together in a seamless environment. When interoperating simulators together, common issues occur frequently due to the simulators handling things slightly differently. These network issues can be overcome by implementing the MAF DMO interoperability standards, which provide a set of specifications defining the technical requirements for VAR. Performing VAR training over a network require significant preparation in terms of time and support personnel. Additionally, the availability of flight simulators (aircraft tanker and aircraft receiver) dedicated to VAR training is also limited and often requires advanced planning.

Another approach to conducting VAR training would be to use constructive aircraft instead of flight simulators. The first generation of simulators for aerial refueling training were designed as stand-alone systems. Stand-alone training is useful but has its limitations because this type of aerial refueling training is usually conducted using a synthetic environment with the capability of generating constructive entities that will perform the role of either aircraft tanker or aircraft receiver. For this type of training, the pilot students fly the simulator and learn to perform the task of either receiving fuel from the constructive aircraft tanker or giving fuel to the constructive aircraft receiver. The use of constructive aircraft tankers or constructive aircraft receivers for VAR training is limited because constructive aircraft are usually designed to fly almost perfectly, which is not realistic. Additionally, when the constructive aircraft is employed as the aircraft tanker, the movement of the flying boom during the AAR operation is not emulated realistically. Therefore, this type of training does not provide the required fidelity for a high level of training transfer. To ensure a positive training transfer when using constructive aircraft for VAR training, the fidelity of the constructive aircraft must be enhanced, especially when the constructive aircraft had the role of the aircraft tanker. For instance, the flight dynamics of the constructive tanker must be enhanced to take the effects of disturbance (e.g., tanker wake and atmospheric turbulence) into account. Additionally, the flying boom movement must reflect the refueling procedure realistically.

Previous Works

VAR training over a network is not new. In fact, high-fidelity VAR training have been successfully performed since 2013 by using flight simulators dispersed geographically—a C-17 flight simulator receiver in Texas, a KC-135 flight simulator in Florida, and a boom operator in a Boom Operator Weapon System Trainer (BOWST) simulator in Oklahoma (Schwindt and Engler, 2014). The VAR exercise was performed via the Mobility Air Force (MAF) DMO Unclassified Network (UCN). Porath and Schwindt published a study in 2016 that described a standards-based approach to implementing VAR in the DMO environment. This study mainly focused on the aspect of networking interface and establishing interoperability standards to enable distributed VAR when flight simulators are located at different geographic locations. The most important factors affecting VAR training were provided in a comprehensive study recently (Tramsposh and Schwindt, 2018) that discussed the physics of model fidelity, data self-consistency and accuracy, and quantitative analysis to enable VAR over a DMO network. Additionally, it provided the most critical lessons learned from conducting a VAR. Nonetheless, these studies employed all virtual simulation, therefore, the fidelity of human performance during the training is guaranteed as both the aircraft receiver and the boom are controlled by pilots and boom operators, respectively. However, there is a lack of the required high fidelity for the case when only one flight simulation is used, as either the aircraft receiver or aircraft tanker, and the other role fulfilled by a constructive simulation. Because of the lack of fidelity of the constructive simulation—especially the lack of realism of the flying boom movement during the pre-contact phase and upon disconnect—this type of training does not provide the required fidelity for a high level of training transfer previously discussed.

To address the lack of fidelity during VAR when only one flight simulator is used as the aircraft receiver, it requires enhancement of the realism for the boom operator. Smith and Kunz (Smith & Kunz, 2006) proposed a precision modeling and simulation of the refueling process between a KC-135 tanker aircraft and an unmanned aircraft. This study provided coupled equations of motion for the refueling boom, modeling its motion and dynamic interactions with the tanker. However, because it was developed for an unmanned receiver, the realism of the boom movement is not critical in this application. In another study, Wang et al. (2017) formulated an attitude controller for a flying boom using the Sliding Mode Disturbance Observer (SMDO) principle, and then a back-stepping controller was used to control the boom attitude. While the main contribution of this study was the construction of a mathematical model for designing control laws to control the boom attitude during an AAR, especially with disturbance such as tanker wake and atmospheric turbulence that can disturb the motion of the flying boom, this study did not address the action of the boom operator during an air refueling mission.

The USAF Aeronautical System Center, Training System Product Group initiated a 3-month study to determine the feasibility and benefits of a common aerial refueling simulation module (Gerken & Ison, 1999). This study included the cost-analysis benefit, a reusable software assessment, a commonality assessment, and many more factors. The list of software that the authors examined in this effort included the "Digital boom operator" module. However, this digital boom operator software focuses solely on the simulation of the boom states, control, and commands rather than the simulation of the boom movement and procedures.

In summary, until now no studies have been designed with the main objective of emulating the actions of a boom operator to enhance the realism of the movement of the flying boom prior to, during, and upon disconnect of a VAR training where a constructive aircraft played the role of the tanker.

METHOD

Rule-Based Expert System – Boom Operator

The rule-based expert system is the simplest form of AI. This system uses rules to represent the knowledge and expertise of subject matter experts (SMEs) (Durkin, 1994). The process of developing a classical expert system is illustrated in Figure 1. Knowledge engineers establish a dialogue or interview with a SME to find out how a particular system is operated. The next step is to determine what reasoning method the SME used to handle facts and rules and decide how to represent them in the expert system. The goal is to capture the experts' knowledge and then encode it to construct the rule-based database. The SME reviews and evaluates the rule-based database to provide any necessary adjustments. This process goes through many iterations until the knowledge rules set is completed (Ligęza, 2006).

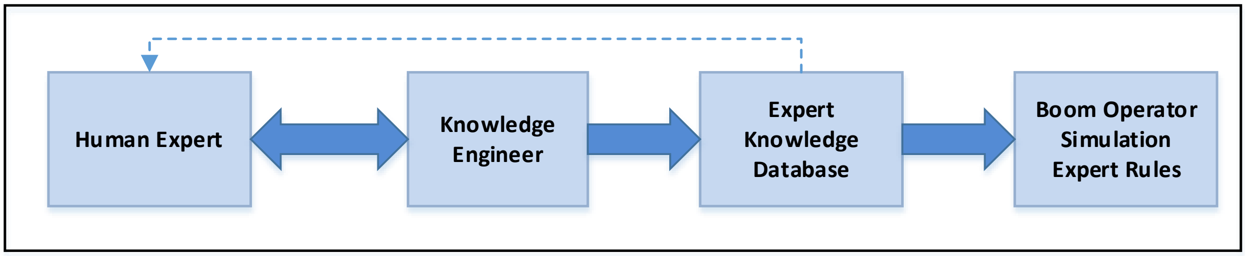

Figure 1. Development of an Expert System – Boom Operator

A rule-based system consists of a set of "IF-THEN" rules, a set of facts, and an interpreter controlling the application of the rules, given the facts. Generally, any rule-based system consists of a few basic and simple elements, such as:

1. A set of facts – The facts are assertions relevant to the beginning state of the system.
2. A set of rules – The rules represent all actions that should be performed within the scope of the problem.
3. Termination criteria – The criteria represent that the conditions of the solution have been found and the appropriate actions can be taken.

It is important to note that the rule-based system should contain only relevant rules. Irrelevant rules affect the performance of the system and should be avoided.

The validity of the rule-based expert system is founded on the fact that when exposed to the same situations, the SMEs usually perform the same operation in the same manner. Because rule-based systems technique encodes the expertise captured from the SMEs, these systems can emulate the operations that the SMEs will perform if facing the same situation.

This study proposed to use a rule-based expert system to emulate the operations of a boom operator during VAR training. This approach will enable the enhancement of realism when a constructive tanker is employed instead of a flight simulator with a human-in-the-loop boom operator. For this reason, this approach will contribute to improving the VAR training transfer.

Emulation of a Boom Operator with Rule-Based Expert System

As mentioned previously, VAR training is ideally performed with flight simulators for both receiver and tanker roles. In the case of VAR using a constructive tanker equipped with a flying boom system, the realism of the flying boom prior to, during, and post fuel transfer from the tanker to the receiver is critical for training.

To model and simulate the flying boom system, we considered the following simulation parameters:

Boom simulated outputs

a. Attitude (Yaw & Pitch)
b. Extension
c. Pilot Director Lights

Boom simulated inputs

a. Distance of receiver
b. Closing velocity

Boom envelope (dictated by receiver limitations)

a. Yaw [-10 degrees (deg.), 10 deg.]
b. Pitch [20 deg., 40 deg.]
c. Command Yaw and Pitch rates are limited to 100 deg./sec.
d. Extension [0 ft., 20 ft.]

To emulate a boom operator, a SME boom instructor was interviewed to capture his expert's knowledge of how a SME operates the boom system during an AAR mission. After several iterations of adjustment, we derived the following set of rules:

1. When the receiver is 1 mile away, the boom operator will hold the boom at 30 deg. and 10 ft. extension until the receiver acquires the astern position (~50 ft. behind the boom nozzle).
2. When the receiver is in the astern position, the boom operator will activate and hold the PDL fly forward (steady) light to begin moving the receiver to the contact position.
3. If the receiver is approaching too fast, the boom operator will start flashing the PDLs to slow down the receiver.
4. The boom operator may use PDL fly forward, aft, up, or down light during the receiver's approach to contact.
5. When the receiver is about 30 ft. away, the boom operator will move the boom to track and align with the receptacle. Alignment for fighter aircraft may start a bit later due to avoiding contact with canopies.
6. As the receiver starts to move to the contact position, the boom operator will start flashing the PDL. Flashing the Forward PDL usually occurs at approximately 10 ft from the contact position for receiver to make smaller corrections.
7. When the receiver is within reaching distance (~ 3 ft extension required), the boom operator will stop flashing PDLs, the receiver will stabilize and hold the position, and the boom operator will be extended to the boom for contact.
8. While in contact, the boom operator will only follow the receiver with the ruddervator control stick to keep the boom aligned with the receptacle.
9. PDLs are automatic once contact is achieved, and the boom operator will no longer control the lights. The lights that are turned on are dictated by the receiver's position. PDLs follow boom movements; if the boom is proper aligned, the PDL's will give an accurate position. If the boom operator does not follow receiver's movements with the ruddevator control stick, then the PDL's will reflect an inaccurate boom position or receiver position. This usually occurs only with student boom operators.
10. Rate of movement toward any limit and while in any non-standard refueling configuration (Manual Boom Latching (MBL) or Tanker Manual Override (TMO) without disconnect capability), the boom operator will ask for disconnect before any limit is reached since while in these configurations the boom operator does not have disconnect capability.
11. At any type of disconnect, the boom operator will raise the boom to at least 22-24 degrees (more if the receiver is high) and retract the boom completely so the PDLs signal a "fly down and back" command.
12. If a breakaway or practice separation is called:
    - The tanker will speed up, the boom will retract to 0 ft. extension and hold at 22-deg. elevation until the receiver is clear.
    - The boom operator will flash the PDL lights (background and direction).
    - The tanker will turn on lower strobe red light (turned on by tanker pilots).
    - When the receiver is ~100 ft. from the tanker, the tanker will slow back down to air refueling speeds, and the boom will be flown back to 30 deg. and 10 ft. extension.
    - The boom operator will stop flashing PDLs; PDL lights will reset so only the background lights are turned on; direction lights will not come on until activated by the boom operator.
    - Boom may fly the boom up higher than 22 degrees, toward the 0 degrees, to help the tanker accelerate away quicker, no specific degrees for a breakaway just clear the receiver.

The set of rules was subsequently reviewed and validated by nine other KC-135 boom instructors. All the boom instructors believed that the set of rules accurately reflected what a boom operator does during an AAR mission.

EMULATION OF A BOOM OPERATOR – SOFTWARE IMPLEMENTATION

To prototype the boom operator emulation, the expert rules described in the previous section were implemented within a simulation of a constructive KC-135 tanker. Two state-machine algorithms were derived from the expert rules. The first algorithm represents the states of the boom operator prior to, during, and after the AAR operation. The second algorithm implemented the state of the PDL lights during the AAR operation. The receiver pilot is required to follow the PDL light indicators to fly the receiver aircraft to the AAR position, so the boom operator can connect the flying boom to the receptacle of the receiver aircraft. Figure 2 and 3 depict the state-machines of the boom operator and the PDL lights respectively.

The simulation of a KC-135 constructive tanker runs in a stand-alone computer and interfaces with an MC-130J flight simulator via a Distributed Interactive Simulation (DIS) network. In order to accomplish VAR over a DIS network, the architecture interfaces must comply with USAF MAF DMO protocol (MAF DMO, 2016), so both the tanker and the receiver have a common interface so they can interoperate. Furthermore, all data are required to export to the DIS network to support visually seeing the aircraft and their articulations, feeling the wakefield, and most importantly, transferring fuel.

It is beyond the scope of this paper to describe in detail the Protocol Unit Data (PDU) employed by the MAF DMO standard. Readers who are interested in more detail can refer to the DIS and MAF DMO standards (IEEE, 2012; MAF DMO, 2016). Only the most critical PDUs pertinent to VAR training are briefly described here:

- Logistics PDU – This PDU contains the data pertinent to the service request, resupply offer, resupply received and resupply canceled.
- Entity PDU – This PDU contains the entity state information. Data such as position, velocity, and orientation are encoding in this PDU. The data pertinent to VAR in this PDU are the appearance and articulation of the entity.
- Collision PDU – The Collision PDU uses to describe contact between the tanker and receiver. The receiver sends the collisions to let the tanker know that contact has occurred, fuel flow is possible, and can be started.
- Data PDU – The Data PDU uses to pass information about fuel flow and wakefield effects. The tanker simulation software will broadcast both sets of data.

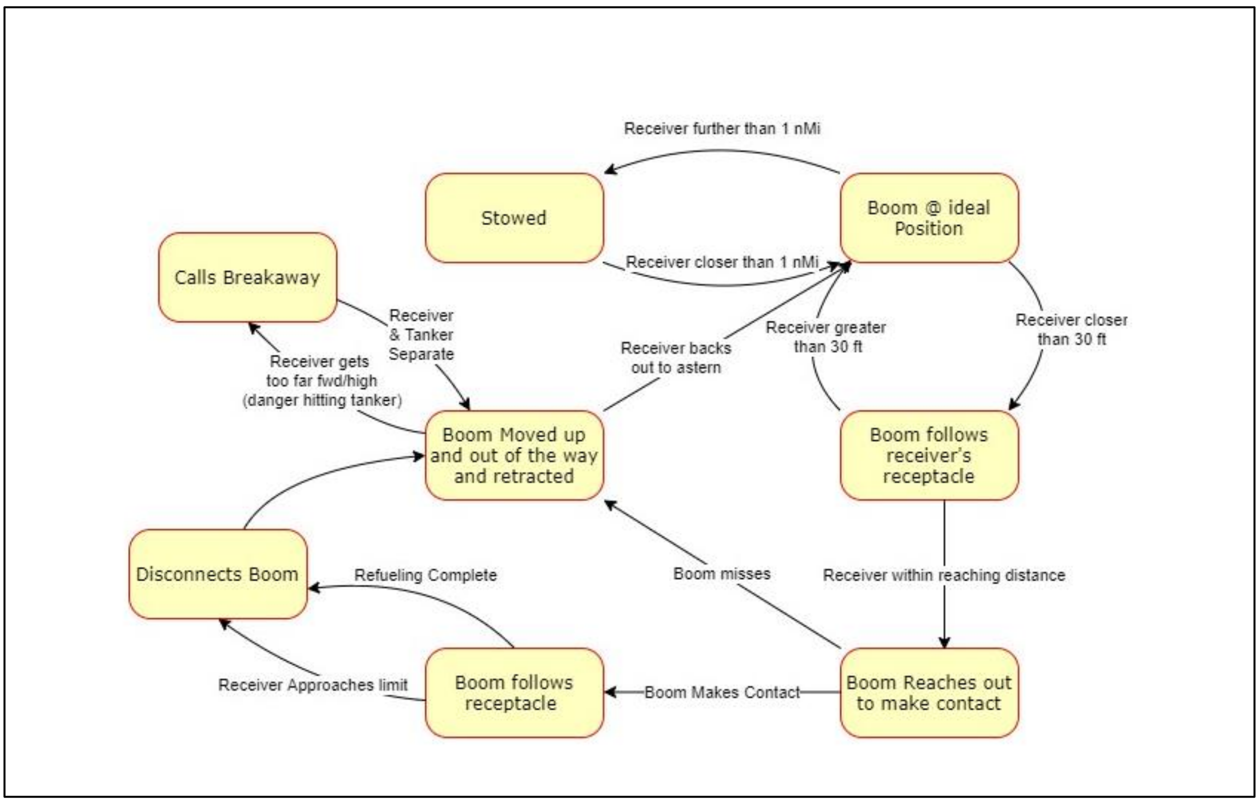

Figure 2. Boom Operator State-machine Diagram

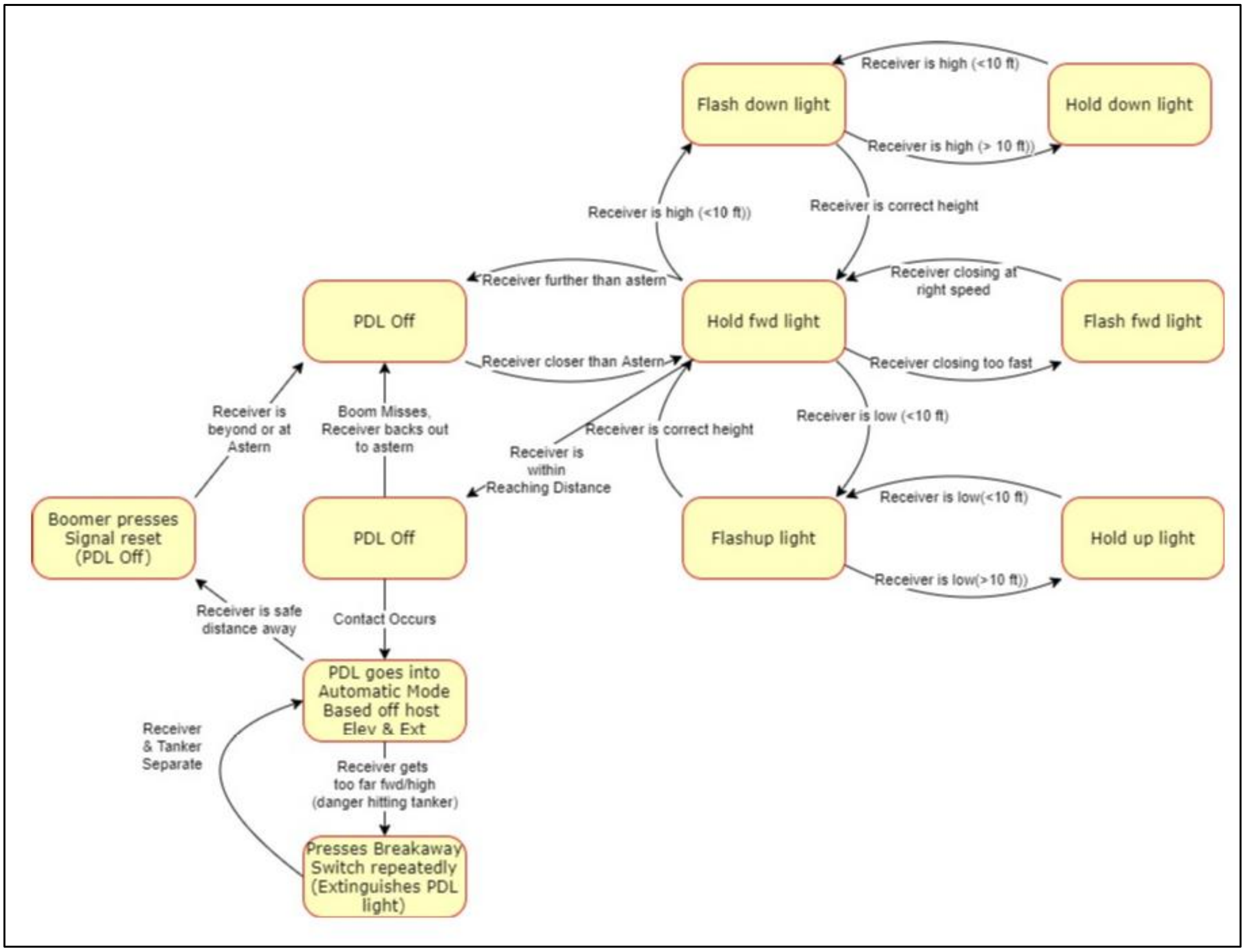

Figure 3. Pilot Director Lights State-machine Diagram

SIMULATION SCENARIO

In order to evaluate the rule-based system emulating the boom operator, a VAR scenario was performed. Both aircraft performed an RV Echo AAR procedure. When the scenario was initialized, the constructive tanker heading was set at the receiver heading plus 90 degrees at a separation of 80 nmi. The synthetic tanker was programmed to fly a racetrack pattern and return to the RV datum every 15 minutes. This RV Echo scenario is illustrated in Figure 4. The scenario was performed twice—the first run without crosswind and the second run with a cross-wind of 20 knots.

The aircraft receiver flight simulator, controlled by a former C-130J pilot (i.e., man-in-the-loop), proceeded to fly towards the RV. As soon as the receiver reached the RV datum, it acquires the same track as the tanker. As the receiver saw the tanker abeam, the receiver proceeded to get into the observation position at the left's tanker side (i.e., echelon left position). The echelon left position was behind the wingline of the tanker. At that point, we considered the RV as successfully performed by the receiver. Subsequently, the receiver proceeded to the astern position. This position was approximately 50 ft. behind and slightly below the tanker boom nozzle where the receiver stabilized at a zero rate of closure before being cleared to the contact position. Next, the receiver proceeded to the contact position. The scenario was considered a **success** when the receiver made it to the contact position and the boom was inserted into the receiver receptacle, making contact. Finally, when the fuel transfer ended, the receiver moved back to the astern position. When the receiver had successfully made it back to the astern position, we considered it represents a **successful disconnection**. In both situations (e.g., contact and disconnect), the boom movement was observed to follow properly the expected expert rules.

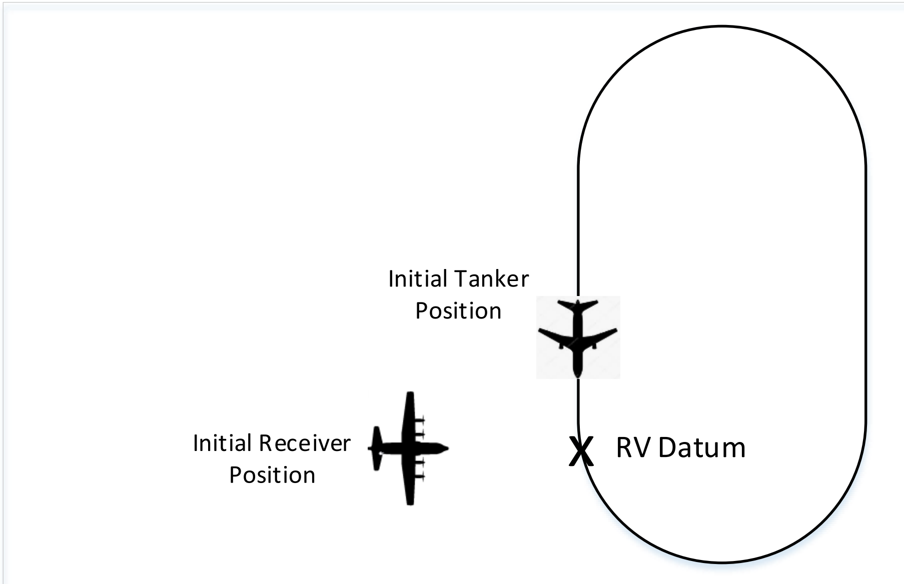

Figure 4. Aerial Refueling Scenario – Echo Rendezvous (RV)

Figure 5 Left presents the visual out-the-window (OTW) display from the receiver aircraft when it was at an astern position, and Figure 4 Right presents the OTW display when the receiver is connected with the boom.

Figure 5. Out-the-Window Views from the Aircraft Receiver Astern (left) and Connection (right)

RESULTS AND DISCUSSION

The software implementation of the boom operator was first validated: during the AAR scenarios, the flying boom movement was visually recorded from the view of the receiver pilot. Each state of the boom movement was subsequently validated by comparing with the AAR expert rules to ensure that the boom emulator software produced the expected results. In this case, the boom motion and the state of the PDL light should reflected the rules as implemented by the state-machine illustrated in Figure 2 and 3.

To evaluate the performance of the boom operator emulation, the pilot was asked to perform this same AAR scenario ten times. A five-minute break was allowed between trials. The average time that took the pilot to fly the C-130J from the astern position to the connection position and make a successful connection with the boom was approximately 47.3 seconds with a standard deviation of 5 seconds. This value is within the range of the values figured in the C-130J Flight Manual (USAF Series C-130J Aircraft. Flight Manual). This result demonstrated that the VAR training using a high fidelity of a boom operator emulation produced equivalent performance when comparing to real-life AAR operation.

Finally, the video recording was showed to a group of former C-130J pilots. Their subjective evaluation of the boom operator simulation was very positive and the pilots acknowledged that the boom operator emulator algorithm did enhance the realism of the flying boom movement and procedure during the VAR training.

In summary, the simulation results of this study demonstrated that by using the rule-based expert system technique, the simulation could realistically reproduce the movement of the flying boom as it was controlled by a boom operator. Combining these simulation results with the utilization of a flight simulator as the role of receiver aircraft meets the simulation fidelity required for a distributed VAR training.

CONCLUSION AND DIRECTION FOR FUTURE RESEARCH

Aerial refueling has been a critical capability to increase the range and endurance of the aircraft; however, the operation is complex and requires significant training. While aerial refueling training conducted with flight simulators provides several advantages and a significant reduction in the cost of training, a positive training transfer must be ensured. Therefore, simulation must be designed with high fidelity to replicate the VAR procedure. This paper presents a novel approach to enhance the realism of the flying boom movement of a constructive tanker during a VAR training. The main contribution of this study is to document the actions that a boom operator performs to control the flying boom attitude and extension prior to, during, and upon disconnect. Additionally, the action of the boom operator was subsequently used to derive a rule-based expert algorithm and implement it into a simulation of a constructive tanker.

Because the boom motion and orientation are known to change the trim of the tanker aircraft during contact, further enhancement to the boom simulation will be necessary to reproduce the dynamic interaction of the receiver aircraft, the refueling boom, and the tanker aircraft. Tanker wake and atmospheric turbulence can disturb the motion of the flying boom; therefore, additional controls of the flying boom attitude will be required to enhance the emulation of the boom operator. Another factor related to the boom movement is when the boom extension extends, the inertia property of the flying boom will change. This factor will briefly affect the movement of the flying boom as the aerodynamic force and moment changed. An experienced boom operator will know how to compensate to minimize this effect. Future work consists of simulating this effect to enhance the realism of the boom movement.

Finally, the SME boom instructors suggested additional features to the simulation, if implemented, would further enhance the realism of the boom simulation. One of the suggested features is to add the level of competency of the boom operator (e.g., competency Level 1-5). This capability will make the VAR training less predictable and more challenging for the receiver aircraft students during training.

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