An Emulation of a Flying Boom Operator: The Dynamic Effects

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ABSTRACT

Aerial refueling is 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 that can generate constructive entities to perform the role of either aircraft tanker or aircraft receiver. When the simulator is used as the receiver aircraft, a constructive aircraft is simulated for use as the tanker or vice-versa. However, the use of a constructive aircraft tanker equipped with a flying boom refueling system will be limited if there is a lack of realism in 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, the authors developed an artificial intelligence (AI) approach to emulate the actions and procedures that flying boom operators would perform during AAR missions ("An Emulation of a Flying Boom Operator Using a Rule-Based Expert System," I/ITSEC 2021). The main contribution of that study was to document the actions that a boom operator performs to control the flying boom attitude and extension before, during, and upon disconnect. Additionally, the actions of a boom operator were subsequently used to derive a rule-based expert algorithm and implement it into a simulation of a KC-135 constructive tanker. The dynamic effects of the boom motion and orientation are known to change the trim of the tanker aircraft; therefore, further enhancement to the boom simulation was necessary to reproduce the dynamic interaction of the refueling boom, the tanker aircraft, and the receiver aircraft. This paper introduces the dynamic effects due to the interaction of the boom and tanker in the simulation of the boom operator. The simulation results demonstrated an enhancement of the realism of the flying boom movement, both visually and operationally.

ABOUT THE AUTHORS

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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:

1. Command and Control (C2) capabilities, including the Tactical Air Control System
2. Intelligence, Surveillance, and Reconnaissance (ISR) and reconnaissance capabilities
3. USAF force application capabilities
4. USAF force projection capabilities
5. 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 the 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 and inserted into the refueling receptacle on the receiving aircraft. The boom is retractable when not in use. The second method of AAR—the P&D system—uses a trailing hose with the basket on the end and 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. For the flying boom refueling system, the boom operator of the aircraft tanker must guide the boom to the receptacle of the receiver aircraft. 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.

Using a flight simulator as the receiver aircraft enables the student pilot to learn the following operations:

- Familiarity with AAR procedures 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 to and during a refueling operation
- Receiver sequence during a refueling operation
- Boom signal and tanker Pilot Director Lights (PDLs)
- Post refueling and reform

The current study proposes to use an artificial intelligence (AI) approach to emulate the actions of a flying boom operator. The algorithm to emulate the actions and procedures of a boom operator was derived from the knowledge of a subject matter expert (SME) KC-135 operator. This AI technique is known as a "rule-based expert system," which represents an "effect-based" system because it is based on the performance aspect of a human operator. The simulation results, when taking into account the dynamic effects of the boom movement prior to, during, and upon disconnect, demonstrated that it is possible to reproduce the realistic 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 the KC-135 burns over 4000 lbs. of fuel per hour. The cost to fly a KC-135 tanker aircraft is approximately $13K per hour. Depending on the type of aircraft receiver, the cost to operate it can vary between a couple of thousand dollars to $50K per hour. While the overall cost of fuel for an air refueling training mission is not exorbitant, it requires an extensive support package 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 of dollars 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 capability 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 training are applied to the real situation (Allen, Hays, & Buffardi, 2001; Noble, 2002). The fidelity of the equipment used for the training and the environment in 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, 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 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 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 Mobility Air Force (MAF) DMO interoperability standards, which provide a set of specifications defining the technical requirements for VAR. Performing VAR training over a network requires 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 was 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 has 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.

Related Works

VAR training over a network is not new. In fact, high-fidelity VAR training has 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 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 is 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, enhancement to the realism for the boom operator is required. 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 disturbances, 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.

METHODOLOGY

A two-phase project was designed to emulate realistically a KC-135 boom operator. The project consisted of:

1. Modeling and simulation of the actions and procedures that flying boom operators would perform during AAR missions using an AI approach, and
2. Introducing the dynamic effect due to the interaction of the boom and the tanker

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

The actions and procedures of a KC-135 boom operator would perform during an air refueling operation were documented in last year's paper "An Emulation of a Flying Boom Operator using a Rule-based Expert Systems (I/ITSEC 2021)." Briefly, a rule-based expert system was developed to emulate the action of a boom operator. The rule-based expert system represents the simplest form of AI. This system uses rules to represent the knowledge and expertise of 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, a human expert, 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).

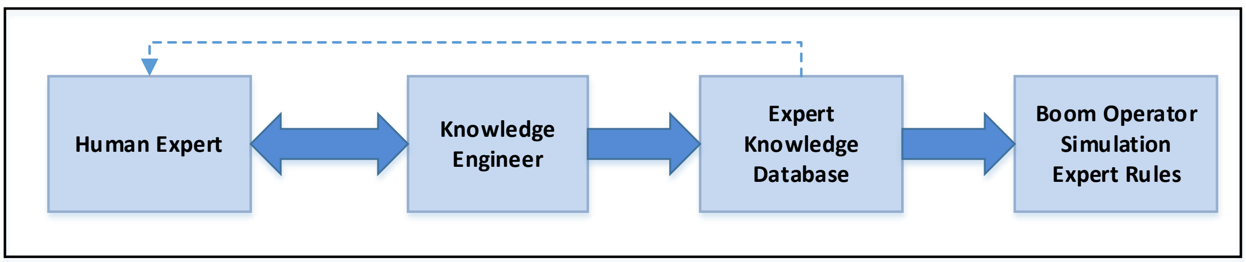

Figure 1. Development of an Expert System – Boom Operator

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 the rule-based system technique encodes the expertise captured from the SMEs, these systems can emulate the operations that the SMEs will perform if facing the same situation.

To emulate a boom operator in this study, a SME boom instructor was interviewed to capture his expert knowledge of how a SME operates the boom system during an AAR mission. After several iterations of adjustment, a final set of rules was derived to emulate a KC-135 boom operator.

Readers who are interested in more detail can refer to last year's paper for additional details regarding the methodology, software implementation, designed simulation scenario, simulation results, and validation of this model.

Emulation of a Flying Boom Operator – The Dynamic Effects

The simulation model as documented in last year's paper consists of a high-fidelity model of the KC-135 tanker and the emulation of the boom operator. However, these models were "uncoupled," that is, the dynamic of one does not affect the dynamic of the other. To enhance the realism of the simulation model, the dynamic interaction between the tanker aircraft and the receiver aircraft needed to be accurately represented. Because the boom motion and orientation were known to change the trim of the tanker aircraft during the refueling process, further enhancement to the boom simulation was necessary to reproduce the dynamic interaction of the receiver aircraft, the refueling boom, and the tanker aircraft. Tanker wake and atmospheric turbulence can also disturb the motion of the flying boom; therefore, additional controls of the flying boom attitude were required to enhance the emulation of the boom operator. Another factor related to the boom movement was when the boom extends, the inertia property of the flying boom changed. This factor briefly affected the movement of the flying boom as the aerodynamic force and moment changed, which in turn affected the dynamic of the aircraft tanker.

Although it is beyond the scope of this paper to detail the development of the coupled dynamic equations of the tanker and the flying boom, the implementation of these equations of motion for the refueling boom that simulated its motion and its dynamic interaction with the tanker can be summarized as follow:

- The equations of motion of the aircraft tanker and the refueling boom were first derived independently from each other. Those equations were subsequently coupled to form another system of equations by employing an implementation of joint coordinates and the velocity transformation (Jerkovsky, 1973; Kim and Vanderploeg, 1986).
- The KC-135 aircraft tanker was modeled as a rigid body. The six degrees of freedom equation of motions were derived by considering the aerodynamic force and moment vectors on the right-hand side as functions of the speed and displacement of the aircraft tanker.
- The KC-135 aerial refueling boom was modeled as two rigid bodies: a fixed boom and a boom extension that is connected. The assembly was attached to the aircraft at the boom root. The fixed boom was tube-shaped, 27.75 feet long, and attached to the aircraft by the boom fork, which enabled the yawing and pitching movement during the refueling process. Two control surfaces, known as the ruddevators, were attached to the end of the fixed boom. These surfaces were what allowed the boom operator to manually fly the boom to the receiver aircraft's receptacle. The origin of the boom extension was located at the inboard end of the boom extension. The axes of the boom extension were always aligned with the fixed boom axes. Therefore, the boom extension telescoped in the direction of the x-axis.
- The mass and inertia properties for the fixed boom were first derived, then moments of inertia for the fixed boom were calculated. The model assumed that the origin of the coordinate system associated with each ruddevator was on the fixed boom centerline, where the pitch axis intersects it. Consequently, the forces and moments on the ruddevators were calculated from blade element theory. The mass and inertia properties of the boom extension were derived from the weight breakdown data of the roller, tube lining, and nozzle shock absorber. The moments of inertia for the boom extension are calculated assuming that fixed masses were point masses. Therefore, the calculation of the forces and moments due to gravity were straightforward based on their position.
- Finally, the tanker and the boom equations of motion were coupled together using joint coordinates and the velocity transformation. The simulation model was updated with respect to the following parameters:
    - Lift Coefficient (Boom Elevation and Receiver relative location on X and Z-axis)
    - Pitching Moment (Boom Elevation and Receiver relative location on X and Z-axis)
    - Side Force Coefficient (Boom Azimuth and Receiver relative location on X, Y, and Z-axis)
    - Rolling Moment (Boom Azimuth and Receiver relative location on Y-axis)
    - Yawing Moment (Boom Azimuth and Receiver relative location on Y-axis)

Software Implementation

For a quick overview, 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. The DIS network complies with the USAF MAF DMO protocol (MAF DMO, 2016), so both the tanker and the receiver can interoperate properly.

The simulations were designed to study the effect of coupling the boom and the tanker. To do so, we updated the simulation software so the dynamic effect can be turned ON (coupled mode) or turned OFF (uncoupled mode) during the simulation. The simulations were performed at two different altitudes: 16000 ft and 25000 ft and at six different tanker airspeeds: 220, 230, 240, 250, 260, and 270 KTS. For each test case, the synthetic aircraft tanker was set to fly straight level with a constant speed. The boom was initially stowed at an elevation of -10 deg (Note: the flying boom refueling system employs the positive-down axis convention). When the simulation started, the boom was held at its initial position for the first 3 seconds. After the first 3 seconds, the boom elevation was set to lower slowly to reach a maximum of 30.0 deg. When the boom elevation reached 30 degrees, it then slowly moved back up to its initial elevation (e.g., -10.0 deg). The entire simulation lasted 1 minute. Each test case was performed in both modes: first for uncoupled mode and then repeated for coupled mode.

SIMULATION RESULTS AND DISCUSSION

To validate the effect of coupling the boom and the tanker, we compared the simulation results when the coupled mode was turned ON and when it was turned OFF. If the implementation of the dynamic effect was effective, there should be noticeable changes in the dynamic behavior of the tanker due to the boom movement. Figure 2 represents the simulation results obtained with the aircraft tanker flying at an altitude of 16000 ft.

When the boom was deployed, the simulation constantly adjusted the tanker dynamic parameters so the tanker could maintain a constant airspeed and fly straight level (i.e., constant altitude). As expected, we observed that the tanker was pitching up, therefore flying with an angle of attack (AOA) to maintain its altitude. We also observed that the pitch of the aircraft tanker was directly affected by the movement of the boom during the simulation. The effect was small but noticeable.

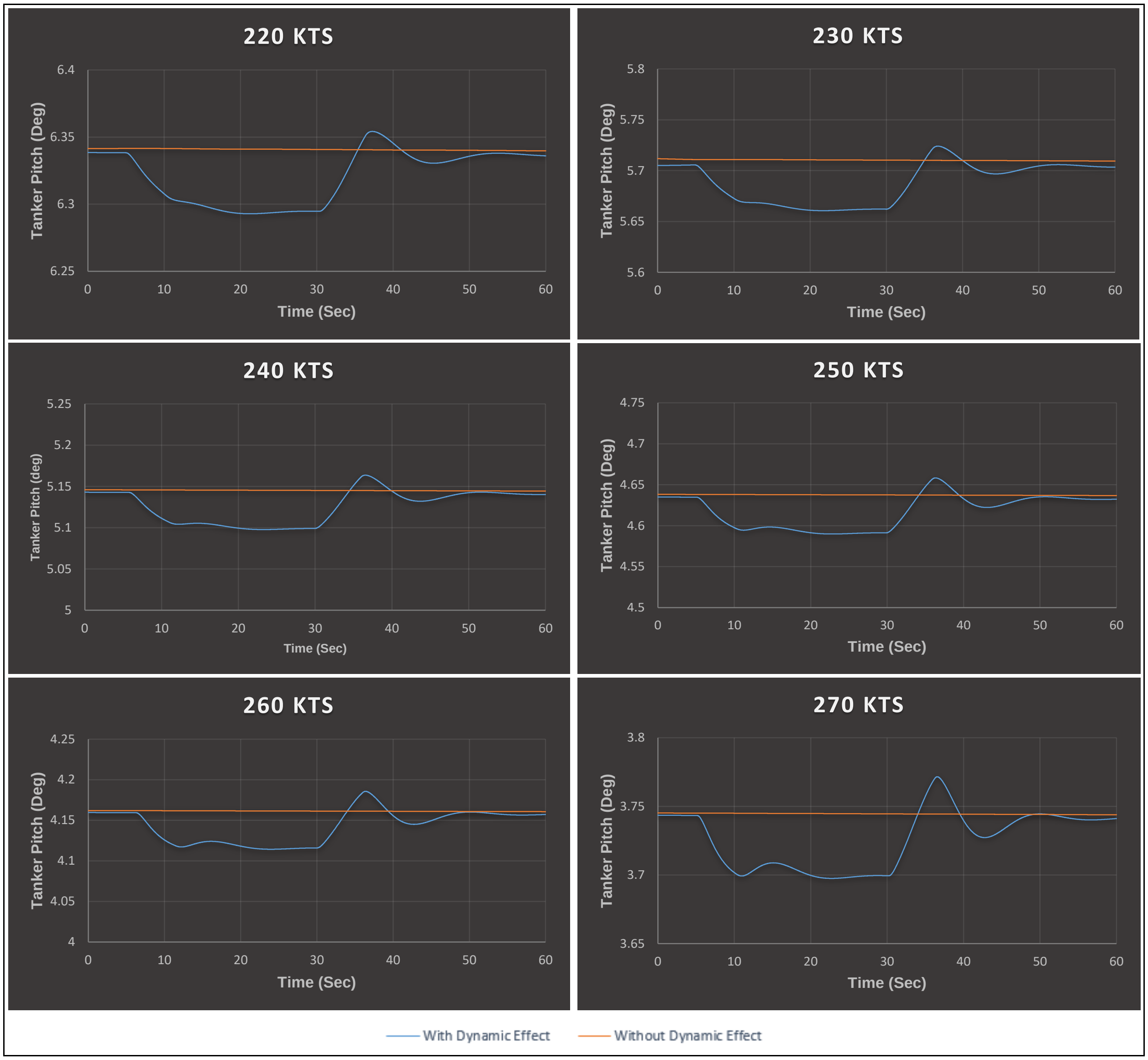

Figure 2. Aircraft tanker pitch obtained for uncoupled and coupled mode at 16000 ft for six different airspeeds (220, 230, 240, 250, 260, and 270 KTS)

Similar results were obtained when the simulation was performed with an altitude of 25000 ft. Figure 3 compares the simulation results obtained at 16000 ft and 25000 ft for two different tanker airspeeds (220 and 270 KTS). While the behavior exhibited similarly, the tanker commanded a greater pitch (therefore the tanker AOA) at a lower altitude. This result was expected.

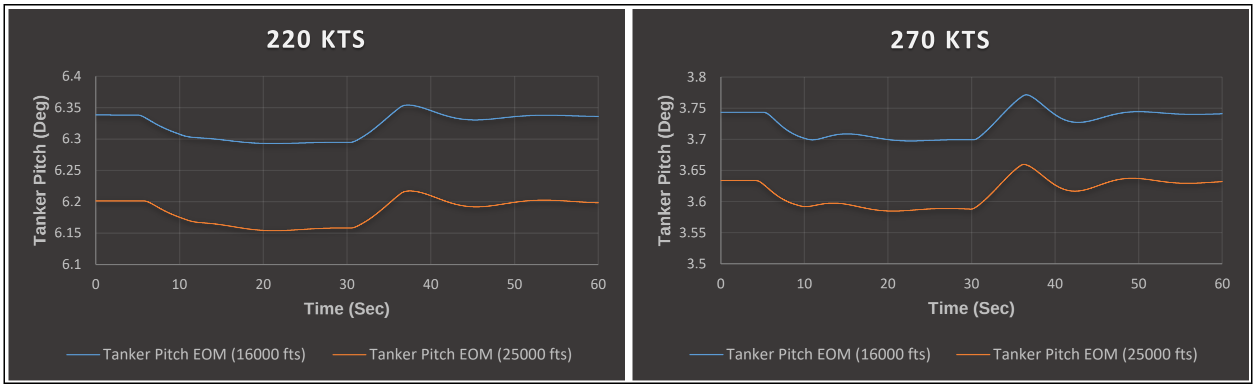

Figure 3. Aircraft tanker pitch at 16000 ft as compared to 25000 ft for an airspeed of 220 KTS and 270 KTS

Another important observation was that for both altitudes (i.e., 16000 ft and 25000 ft), the tanker pitch decreased when the boom elevation increased as shown in Figure 4.

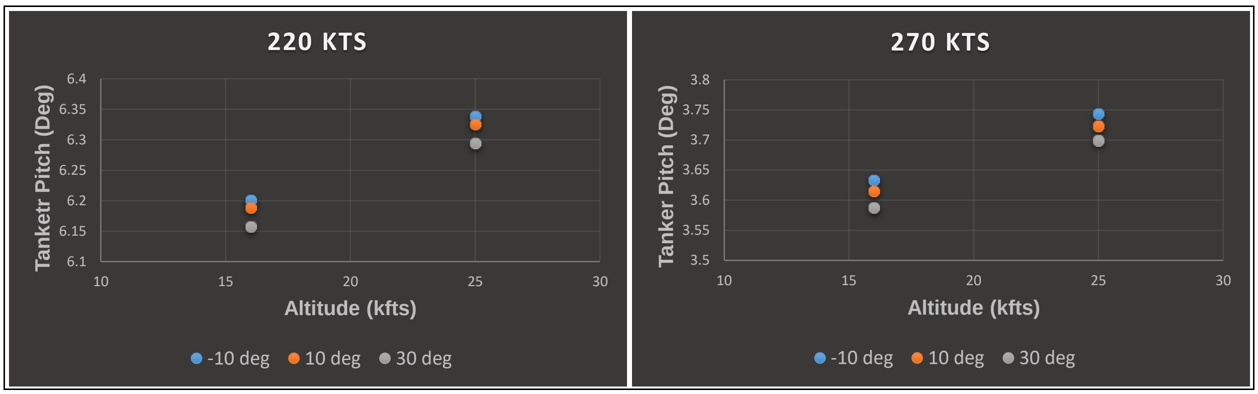

Figure 4. Effect of tanker altitude on the tanker pitch for an airspeed of 220 KTS and 270 KTS

Tables 1 and 2 provide additional simulation results regarding the effect of the tanker airspeed on the tanker pitch as a function of the boom elevation (-10, 0, 10, 20, and 30 degrees).

Table 1. Effect of tanker speed on the tanker pitch as a function of the boom elevation – Altitude 16000 ft

Boom Elevation (Deg)	Airspeed (KTS)					
	220	230	240	250	260	270
-10	6.339	5.705	5.143	4.635	4.160	3.743
0	6.338	5.706	5.143	4.635	4.159	3.743
10	6.326	5.692	5.128	4.618	4.141	3.724
20	6.312	5.679	5.113	4.603	4.125	3.706
30	6.295	5.662	5.099	4.591	4.116	3.699

Table 2. Effect of tanker speed on the tanker pitch as a function of the boom elevation – Altitude 25000 ft

Boom Elevation (Deg)	Airspeed (KTS)					
	220	230	240	250	260	270
-10	6.201	5.567	4.996	4.493	4.045	3.634
0	6.201	5.566	5.002	4.493	4.045	3.634
10	6.189	5.553	4.988	4.476	4.027	3.615
20	6.177	5.540	4.973	4.461	4.011	3.599
30	6.158	5.523	4.958	4.449	3.599	3.588

The simulation results demonstrated that the implementation of the dynamic effect was effective and produced the expected results. However, to ensure that the implemented dynamic effect was valid and performed correctly, the simulation results had to be compared to the actual "flight test" data. This process is known as the "Qualification Test Guide" or QTG. Because it is not possible to present a completed validation QTG data within the limitation of an I/ITSEC paper, we present only a subset of our validation results for illustration purposes.

Table 3 provides the test conditions of the four test cases that we selected to illustrate the validation results. Each selected test case represented a typical phase during a completed air refueling mission.

Table 3. Initial conditions for "Boom deployment", "Pre-contact", "Pre-contact to Contact" and "Boom connected" simulation test cases

Test case	Tanker Airspeed (Kts)	Tanker Pitch (Deg)	Boom position Elevation (Deg) Azimuth (Deg)	Tanker altitude (ft)	Receiver Relative Position (x,y,z)
Boom Deployment	250	3.3	-12.3 0.0	15774	No receiver
Pre-Contact	271	3.3	31.0 0.0	25048	(-50 ft, 1 ft, 10ft)
Pre-contact to Contact	272	2.7	33.0 0.0	25068	(-53.0 ft, 1 ft, 4 ft)
Boom Connected	270	3.2	31.0 0.0	25051	(0 ft, -2 ft, -2 ft)

For each test case, the simulation results of the updated simulation model were recorded and then compared to flight test data for each state of the refueling process (e.g., boom deployment, pre-contact, pre-contact to contact, and boom connected). The validation was focused on the boom attitude and lateral movement and the tanker attitude and its AOA. The performance tests were conducted using the Auto Test System (ATS) resident in the simulator programming. This system controlled the operation of each test by initializing the simulator configuration (e.g., weight, CG), flight condition (e.g., altitude, airspeed), executing an initial trim, then providing control input time histories to the rest of the simulator software. The test results were recorded to disk memory in both the auto and the manual modes. For these cases, aircraft data were simultaneously over-plotted on the same page to easily compare the performance results. For each simulation run, the ATS recorded over 20 tanker physical dynamic parameters, such as the tanker speed, and tanker attitude. The simulation results of these parameters were then compared directly to the actual flight test data of a KC-135 aircraft. The performance was considered "satisfied" if the data was within the allowed tolerance. Otherwise, a tuning process would be required to adjust the performance of the model.

To be consistent with the previous simulation results, we present only the QTG data for the tanker pitch in Figure 4, but all the recorded dynamic physical parameters of the tanker were compared to the actual flight test data to ensure that the dynamic of the simulated tanker performed as expected. According to the KC-135 flight test data, the tolerance for the tanker pitch was approximately +/- 1 degree. The simulation results, as shown in Figure 5, demonstrate that the simulation of the dynamic effect was within the acceptable tolerance when compared to the flight test data.

Finally, we observed minor differences when we compared the simulation data to the flight test data. The flight test data exhibited a constant "varied-adjusted" behavior that did not show in our simulation model. This difference in behavior can be explained by the fact that our simulation did not fully model all the tanker aircraft moving parts and systems, such as auto-pilot, that "retrims" when the forces exceeded the stabilizer. Also, in our simulation model, we assumed an even layout of the fuel, which may not necessarily match exactly the actual KC-135 aircraft fuel configuration when the flight test was gathered.

Figure 5. Tanker pitch as computed by the boom emulator software VS flight test data obtained from a KC-135 aircraft with auto-pilot enabled

CONCLUSION AND DIRECTION FOR FUTURE RESEARCH

Aerial refueling is a critical capability to increase the range and endurance of 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 an approach to enhance the realism of the flying boom movement of a constructive tanker during VAR training. One of the contributions of this study was to document the actions that a boom operator performs to control the flying boom attitude and extension prior to, during, and upon disconnect. Then, 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 were known to change the trim of the tanker aircraft during contact, further enhancement to the boom simulation was 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 as well; therefore, additional controls of the flying boom attitude were required to enhance the emulation of the boom operator. Another factor related to the boom movement is that when the boom extension extends, the inertia property of the flying boom changes. This factor affected the movement of the flying boom as the aerodynamic force and moment changed. The equations of motion of the aircraft tanker and the boom were updated accordingly to take into account these dynamic effects due to the interaction of the boom and the aircraft tanker. The simulation results of this study demonstrated that when the dynamic effects of the boom were updated to the emulation of the boom operator, 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 use of a flight simulator as the role of receiver aircraft meets the simulation fidelity required for distributed VAR training.

Finally, the SME boom instructors suggested additional features for the simulation, which, 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 Levels 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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