Requirements Analysis for the Aircraft Maintenance Training Continuum

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ABSTRACT

The simulation and training industry has decades of experience in specifying and acquiring aircraft flight simulators for aircrew training. This experience, however, does not translate well to deriving requirements for the relatively recent acceptance of virtual maintenance trainers into the industry. In designing a Virtual Maintenance Trainer (VMT), requirements need to be based on the desired level of training for the practical application of the knowledge and skill obtained from the VMT. The aircraft maintenance training continuum encompasses the knowledge domain from the ab initio aircraft maintenance technician to the 20-year seasoned master mechanic. The learning objectives across this continuum are very different; a "one size fits all" set of maintenance training requirements result in unnecessary costs and/or ineffective training scenarios. Today's VMT technology can support a wide variety of requirements regarding procedural fidelity, graphical fidelity, and interactivity methods. Procedural fidelity establishes if a single trainee interaction event is required to remove and replace an entire component, or if the trainee needs to select every individual nut/bolt/washer to complete the lesson. Graphical fidelity ranges from a hand modeled artist renditions of the devices to full CAD data translation of the aircraft systems. Interactivity methods cover the spectrum from a mouse click to fully immersive 3D haptic gloves in a stereoscopic system. The scope of requirements for a specific VMT application should be driven by the specific needs in the training continuum. This will maximize training value while minimizing training costs. This paper reviews the requirements from three different large-scale VMT programs: the Canadian CH-147, Australian F/A-18E, and F-35 JSF. It highlights how the differing requirements are derived to meet the desired training level within the maintenance training continuum. Through this we seek to describe the impacts requirements levy on the cost and complexity of the resulting VMT.

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BRIEF HISTORY OF VIRTUAL MAINTENANCE TRAINING

A Virtual Maintenance Trainer (VMT) combines simulation software with accurate 2D and 3D graphical depictions of a real-world object or craft within an interactive 3D virtual environment; such that maintenance actions including operational checks, troubleshooting, and removal/installation can be performed in the virtual world as they would be performed in the real world. The simulation software and graphical depictions are generally representative of both normal and faulted operation. The capability and cost of a VMT can vary widely depending on the scope (number and complexity) of required maintenance procedures, and required adherence to detailed steps combined with graphical fidelity (level of detail) within those procedures. This paper discusses these considerations, combined with trainee qualifications, in relation to defining VMT specifications for a particular real-world object or craft.

What Drives the Need for VMTs?

There are many reasons for the emergence of the VMT, including the availability of powerful computing and graphics technology, escalating cost of training, compressed training schedules, and increased throughput requirements. From a training perspective, reasons for the use of VMTs have included the needs to more effectively train troubleshooting skills, train more safely, and reach out to a younger pool of potential maintainers. The two most influential contributing factors to the arrival of the VMTs over traditional hardware-based maintenance trainers in the last five/ten years are cost (non-recurring and recurring) and trainee throughput.

With regard to cost, there was a study conducted in 2008 on the 11G2 Desktop Trainer to verify if replacing hardware based maintenance trainers with desktop based versions was financially viable. The conclusion was "the 11G2 Desktop Trainer can increase training efficiency by approximately $100 million over 30 years and reduce trainee's cost by over 29 %" (Duke, Bahlis, and Morrissey, 2008). Another interesting note in this study was that the operational costs of the original hardware training device was $92 USD per trainee hour whereas the operational costs of the desktop training device was $0.12 USD per trainee hour.

Per the U.S. Department of Labor Statistics, employment of aircraft mechanics and avionics technicians is projected to grow six percent from 2010 to 2020, slower than the average for all occupations (www.bls.gov). In short, in order to support an aging fleet of aircraft and an ever-increasing number of aircraft in a fleet, more people need to be trained than there are potential trainees entering an Aircraft Maintenance Training (AMT) program.

How Industry Has Approached Filling This Need

Industry's ability to address this need has been largely driven by three factors: (1) cost, (2) availability of computing and graphics technology, and (3) acceptability of a virtual approach by the end users (Giordano, Jackson, and Blankemeier, 2012).

Prior to graphics-based VMTs, maintenance trainers largely consisted of static or computer-driven hardware replicas, panel boards, and video-based solutions. Hardware solutions were costly both in their initial procurement and on-going support/concurrency upgrades, particularly in areas of frequent aircraft updates, such as avionics. Hardware solutions also had procurement cycles that are 25% to 30% longer due to long manufacturing times, creating delays in getting needed training to trainees more quickly.

Using the F/A-18E Super Hornet maintenance trainers as an example, the hardware-based F/A-18E Maintenance Training System (MTS) fielded in the mid 1990's has remained largely at its original Lot 24 aircraft configuration, primarily due to upgrade cost considerations (Giordano, Jackson, and Blankemeier, 2012). This fueled the initial foray into VMTs for the Super Hornet as a way to upgrade the avionics training to cover Lot 27 aircraft, resulting in the initial development of the F/A-18E Visual Environment Maintenance Trainers (VEMT) deployed in 2006 for Lot 27 and again in 2009 for the Lot 30 upgrade. The VEMT was later upgraded to Lot 30 ensuring that training was keeping pace with the aircraft configuration, unlike the traditional hardware device.

Technology available at the time of VEMT development limited the trainer primarily to the use of 2D interactive graphics combined with photo-based representations of the aircraft. Use of a photo-based approach limited the ability to achieve detailed step-by-step replication of maintenance procedures, particularly in the area of removal and installation of Weapon Replaceable Assemblies (WRA).

It should be noted that around the same time as the VEMT development from 2006 to 2009, the USN F/A-18C Simulated Aircraft Maintenance Trainer (SAMT) broke new ground with implementation of an interactive 3D virtual environment with 3D graphical models of the full aircraft. The SAMT began in 2005. However, due to limitations of then-current computers and graphics cards, the level of fidelity of the aircraft models varied widely between essential virtual objects (i.e., aircraft assemblies the trainee must interact with) and background objects that require no interaction and primarily provide spatial orientation.

Availability of more powerful computers and graphics cards, starting around 2008, combined with the increasing availability of aircraft CAD data, has allowed the VMT industry to eliminate most fidelity and performance issues. Table 1 highlights the differences in graphics card processing capabilities over five years (www.nvidia.com).

Table 1. NVIDIA Graphics Card Capabilities (www.videocardbenchmark.net)

Year	Graphs Card Model	Onboard Memory	Fill Rate Pixels/Sec	Fill Rate Texels/Sec	Memory Bandwidth/Sec	Processing Power
2008	NVIDIA GeForce 8100	512 Mb	2 Giga	4 Giga	6.4 Gb	28.8 GigaFlops
2013	NVIDIA GeForce GTX 780M	4.096 Gb	26.3 Giga	105.3 Giga	160 GB	2234.3 GigaFlops

This step increase in capability (see Figure 1) is appropriately represented by the three programs that form the basis of this study (programs of interest); the F/A-18E Integrated Visual Environment Maintenance Trainer (IVEMT), CH-147 Integrated Display System (IDS), and F-35 Aircraft System maintenance Trainer (ASMT) all described in detail later in the paper. These trainers support high fidelity 3D interactive graphics, and a high level of detail throughout the entire virtual aircraft and suite of support and test equipment, and can support adherence to the step-by-step details of the maintenance procedures at varying levels.

F/A-18C SAMT (circa 2006) F/A-18E IVEMT (circa 2010)

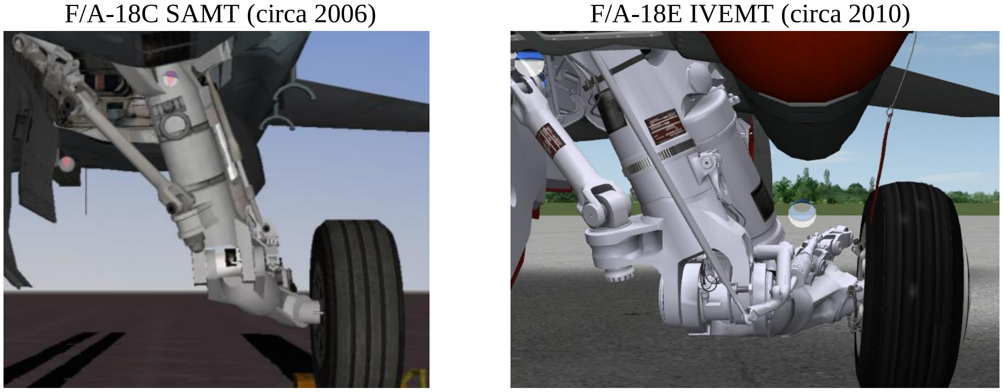

Figure 1. Graphics Capability Comparison

This increased capability has now allowed the ISD professionals to tailor the requirements of VMTs to a wider range of fidelity and performance commensurate with the training objectives, trainee qualifications, and available training time. As an example, if a VMT does not support landing gear maintenance procedures, a simpler level of detail may suffice. However, if the included maintenance procedures require troubleshooting of the landing gear and component removal/replacement, the higher level of detail will be required. The tailoring of requirements will directly drive the cost.

The achievement of high fidelity and real-time performance has also allowed industry to focus on other elements of the VMT, including more immersive virtual environments, and alternate Human Machine Interfaces (HMI), such as game engines, game controllers, advanced haptic feedback devices, mobile training delivery systems, etc. Also, industry is endeavoring to reduce cost through development of flexible Software Development Kits (SDK) and processes that streamline VMT design, development, and testing.

Today, industry offers a wide range of VMT applications and delivery systems to support flexible training approaches, including:

- Standalone, platform level VMTs (entire aircraft or craft)
- Subsystem-level VMTs or lessons
- VMTs integrated with SCORM-conformant Computer Based Training (CBT) / Interactive Multimedia Instruction (IMI)
- VMTs integrated with Intelligent Tutoring Systems
- Networked VMTs that support electronic classroom configurations
- Individual or team training in a common training scenario
- Distributed training
- Use of mobile delivery systems, including iOS, Android, and Windows tablets

THE MAINTENANCE TRAINING CONTINUUM

The field of Aircraft Maintenance is changing rapidly. Increases in aircraft complexity over the years have facilitated a need for more maintainers with greater capabilities and knowledge on these newer systems. AMT programs must continually be revaluated along the entire training continuum in order to narrow the gap between graduate capabilities and industry requirements. Prior to discussing this paper's specific programs of interest and the differing levels of requirements and capabilities, it is best to understand a basic, high-level view of the range of required training from basic to advanced; while remembering that requirements typically change based on the need at a specific point during the training continuum. Figure 2 summarizes the general aviation maintenance training continuum, and shows where the paper's programs of interest fall in that continuum.

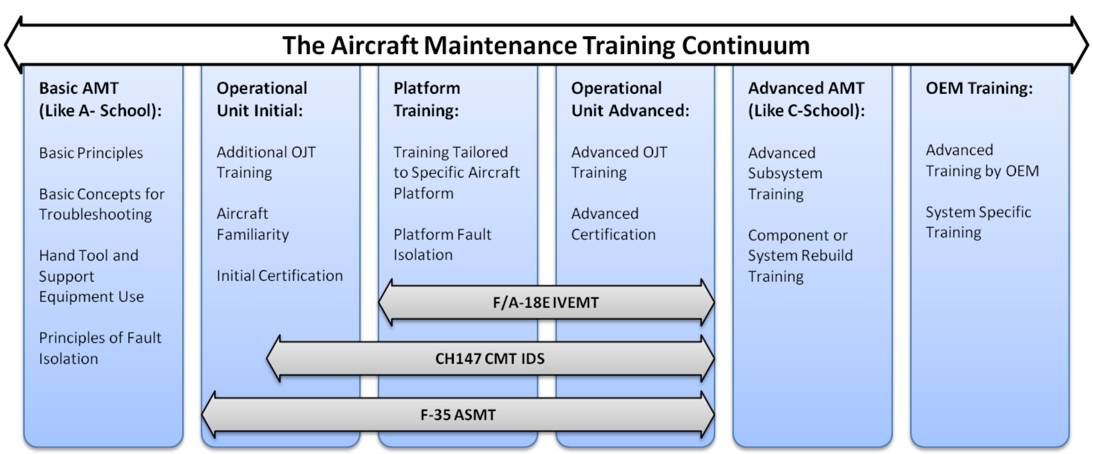

Figure 2. Maintenance Training Continuum

Figure 2 follows a typical aircraft maintenance technician's training from initial schooling, through advanced platform-specific organizational and intermediate training, and on to depot level training on specific sub-systems.

While most countries and services have their own specific career path definitions, Figure 2 is provided as a notional training continuum that can serve as a place holder for where the specific VMT programs of interest discussed in this paper might fit.

Table 2 indicates typical VMT requirements associated with the three areas of the continuum occupied by the programs of interest. Initial training is typified by stricter adherence to detailed steps, manual navigation, and procedural constraints. More advanced training introduces greater free-play capability, auto navigation aids, and condensed procedures with grouped animations to streamline operations.

Table 2. Typical VMT Requirements Across the Continuum

VMT Requirement	Operational Unit Initial	Platform Training	Operational Unit Adv.
Aircraft specific	X	X	X
Full free-play (1)	-	-	-
Limited free-play	-	X	X
Procedural constraints	X	-	-
Manual navigation	X	X	X
Auto navigation aids	-	X	X
Common hand tools (2)	-	-	-
Active support equipment (3)	X	X	X
Full adherence to procedural steps (level of detail)	X	X	-
Condensed procedures, grouped animations (level of detail)	-	X	X
Auto support equipment positioning	-	X	X
Manual support equipment positioning	X	X	-
External power and fuel cart 3D models	X	-	-
Hoists, lifts, crane models	X	X	-
Line Replaceable Unit (LRU) level troubleshooting	X	X	X
LRU removal and installation (4)	X	X	X
Animated Schematics	Optional	Optional	Optional

(1) Effective full free-play may be achieved if a sufficient number of procedures are simulated.
(2) Common hand tools include hammers, screwdrivers, wrenches, etc.
(3) Active support equipment is any item that must be read, adjusted, powered up, etc.
(4) See “Full adherence to procedural steps” and “Condensed procedures, grouped animations” for level of detail requirements.

Cost Drivers

The cost of developing a VMT is driven primarily by three main areas: (1) the number of procedures included; (2) level of level of detail, including graphics fidelity and adherence to step-by-step procedure implementation; and (3) extent of free-play required.

The number of procedures required is a direct function of the training task analysis and media selection by ISD personnel. Increasing the number and extent of procedures (e.g., operational checks, troubleshooting, and removal/installation) will drive the cost of simulation software and graphical object development for both the aircraft and support equipment. However, as the number of procedures reaches a high percentage of the total number of available procedures, the cost per additional procedure is reduced. Essentially, as more of the aircraft and items of support equipment have already been modeled, the changes required to implement additional procedures are minimized.

Level of detail, defined as graphics fidelity and adherence to step-by-step procedures, drives many aspects of the design process and associated cost, including:

- The time to model individual graphical objects

- The number of individual graphical objects that must be separately designed, animated, integrated, and tested
- The Virtual Environment's ability to manage large numbers removed piece parts, and allow selection of those parts for reinstallation

The level of detail also has operational impacts in that the time to execute a specific procedure can be significantly increased as level of detail grows.

The availability and cost of implementing free-play (deviating from supported procedures) can be significant depending on the extent of free-play desired. Free-play is a contributing factor to the required level of detail. Figure 3 illustrates the concept of free-play. The lowest cost approach to implementing the simulation software and graphics in a VMT is generally associated with just implementing the individual procedures without the ability to deviate from the procedure.

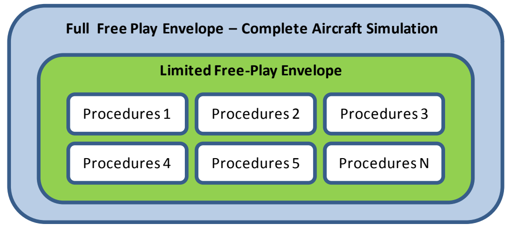

Figure 3. Free-Play Options

Full free-play can be achieved by complete simulation of all aircraft systems with a high level of detail, allowing the trainee to disconnect any connector, probe any pins with correct readings, and remove any LRU, even if those elements are not indicated in the supported procedures. This can be very cost prohibitive and can have limited or even negative training value (see Figure 4).

A reasonable cost alternative is to support a limited free-play capability that is bound by the cumulative functionality derived from all the specified procedures. This offers a limited ability for the trainee to deviate from the established procedure, but with reasonable constraints on how far that deviation may be supported by correct indications. Limited free-play provides positive reinforcement within troubleshooting procedures as they allow the student to see the results of improper interpretation of measured results or incorrect support equipment set-up. Limited free-play also allows the instructor to navigate throughout the virtual aircraft in any sequence to highlight specific areas of interest and procedural subtleties.

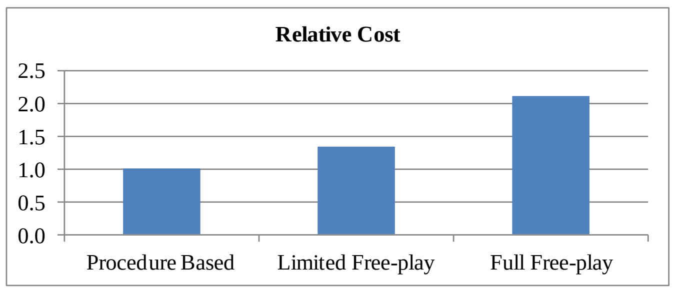

Figure 4. Relative Cost of Free-play versus Procedure-based Approach

PROGRAMS OF FOCUS FOR LEVEL OF DETAIL STUDY

This section highlights the three programs of interest in order to better understand the differences in the level of detail in requirements that may be specified on a program, and the resultant operational impacts. The three programs selected for study each focus on a different initial level of training requirements. The F/A-18E IVEMT program highlights requirements designed for more experienced maintainers. The CH-147 CMT IDS shows requirements for mid-range to more experienced maintainers. Lastly, the F-35 JSF highlights an example of requirements developed for both entry level and experienced maintainers. This does not imply that one trainer is better than the others. Instead, they all have unique requirements and are designed to meet the needs of the maintainer at specific points within the training continuum.

Requirements Variances within the Programs of Interest

Table 3 lists representative requirements across the three programs of interest, highlighting differing implementation approaches to the requirements. Of particular note is the high level of detail required in the F-35 ASMT, particularly related to the adherence to the individual steps of the procedures. These requirements are derived from the individual VMT specifications for the programs of interest, along with actual implementations from the delivered devices. It should be noted, that at a minimum, all studied programs required a level of detail sufficient to perform the troubleshooting procedures that lead to the identification of a failed LRU. Level of detail requirement differences were concentrated in the areas of door/access panel fastener interaction, support equipment staging and set-up, and LRU removal/replacement.

Table 3. Selected Program Requirements

Requirement	USN F/A-18E IVEMT	CH-147 CMT IDS	F-35 (JSF) ASMT
General Fidelity	Fidelity supports condensed procedures and grouped animations to streamline operations.	Fidelity supports condensed procedures and grouped animations to streamline operations.	Fidelity to support every step of every procedure.
Free-play Capability	Free-play limited by the combined functionality of all required procedures. Not constrained to specific procedural sequences. Honors physical constraints.	Free-play limited by the combined functionality of all required procedures. Not constrained to specific procedural sequences. Honors physical constraints.	Free-play limited by the combined functionality of all required procedures. Honors physical constraints. Based on IOS control, operation can be constrained to follow selected scenarios (procedures)
Common Hand Tools	Not supported graphically	Not supported graphically	Not supported graphically
Door/LRU Fasteners	Single click on door with no interaction with fasteners. Limited fastener animation.	Manual interaction with latches and handles. Single step opening of access doors. Full fastener animation.	Click on any one door fastener and all animated loose. Separate action to remove or open door. LRU fasteners must be individually loosened.
Tag-outs	Not required	Tags installed automatically on disconnection	Manually installed
Jacking the Aircraft	Instant install, 2D control panel	Drag to install in correct location, 2D control panel	Deploy to tarmac, individual moved work area, and select location on tarmac hot spot. 3D interaction with Jack controls.
Remove & Install (R&I) of Weapons Replaceable Assembly (WRAs)/Line Replaceable Units (LRUs)	Single click initiation with auto disconnection/animation	Manual disconnect fasteners and cables/lines, then single click to remove the LRU	Manual disconnect of fasteners and cables. Manual disconnect of individual piece parts, including nuts, washers, bolts, cotter pins, etc.
Engine Removal	Supported with condensed procedures and grouped animations	Not supported on VMT. Instead supported on associated Composite Maintenance Trainer	Full fidelity removal procedures supported including hoists, trailer, and truck
Support Equipment Selection	Selected from pop-up menu	Selected from pop-up menu	Check out support equipment from virtual resource list
Support Equipment Staging	Automatic placement	Automatic placement	Staged out to flight line and manually installed where needed
Hoists and Lifts	Not represented	Not represented	Fully implemented in 3D, full 6-DOF control
External power and fuel carts	Not modeled	Not modeled	Modeled and functional in 3D

Level of Detail Analysis

For each of the selected programs a single LRU was selected to demonstrate how the level of detail impacts the operation of the trainer and the trainee experience. The LRUs selected include the F/A-18E On-Board Oxygen Generation System (OBOGS) Concentrator, CH-147 Ramp Control Valve, and the F-35 Drag Brace Actuator. The LRUs were selected primarily due to the comparable number of parts within the LRUs. Though they have roughly the same number of parts, the difference in the process of removing each of the parts, and the times to accomplish that removal are significant. Table 4 shows the number and complexity of the steps associated with the removal of each LRU and the average time to accomplish the removal. The number and complexity of the steps across all procedures drives the level of detail (cost and time to develop), along with the time it takes during the training course to train the procedures; impacting course length requirements.

Table 4. LRU Removal Procedures

	F/A-18E IVEMT	**CH-147 IDS**	**F-35 ASMT**
Step	**OBOGS Concentrator Removal**	**Ramp Control Valve Removal**	**Drag Brace Actuator Removal**
1	Navigate to bay door 13L and open the bay door	Navigate to internal area of the ramp door	Go to the Depot and check out a Spring Compressor Tool
2	Select the OBOGS Concentrator and remove it to the task bar	Remove hydraulic connector valve 1	Load the Spring Compressor Tool into the Staging and Inspection area
3		Remove hydraulic connector valve 2	Pick up the Spring Compressor Tool and carry it to the aircraft in the Virtual Environment
4		Remove hydraulic connector valve 3	Navigate to the left rear landing gear
5		Remove hydraulic connector valve 4	Disconnect Hydraulic Tube Nut and Install Protective Devices
6		Remove hydraulic connector valve 5	Disconnect Down Lock Actuator Lower Hydraulic and Install Protective Devices
7		Remove hydraulic connector valve 6	Disconnect Hydraulic Tube Nut and Install Protective Devices
8		Remove hydraulic connector valve 7	Remove Drag Brace Downlock Actuator Rod End Safety Cable and discard to FOD
9		Remove hydraulic connector valve 8	Remove Drag Brace Downlock Actuator Rod End Nut and Bag & Tag
10		Unscrew one (1) electronic cable harness	Remove Drag Brace Downlock Actuator Rod End Washer and Bag & Tag
11		Remove three (3) Ramp Control Valve Bolts	Remove Drag Brace Downlock Actuator Rod End Crossbolt and Bag & Tag
12		Remove Ramp Control Valve	Remove Drag Brace Downlock Actuator Rod End Pin
13			Remove Drag Brace Downlock Actuator Spring End Safety Cable and discard to FOD
14			Remove Drag Brace Downlock Actuator Spring End Nut and Bag & Tag
15			Remove Drag Brace Downlock Actuator Spring End Tanged Washer and Bag & Tag
16			Remove Drag Brace Downlock Actuator Spring End Crossbolt and Bag & Tag
17			Install Spring Compressor on Actuator
18			Compress Spring
19			Swing Actuator up
20			Remove Spring Compressor from Actuator
21			Remove Actuator from Drag Brace to Work Area
Average Time to Perform			
	6 Seconds	**1 Minute, 14 Seconds**	**3 Minutes, 6 Seconds**

F/A-18E Integrated Visual Environment Maintenance Trainer (IVEMT)

The design of the IVEMT, shown in Figure 5, is a dual screen layout where one screen is an accurate reproduction of the 3D virtual aircraft (on the left in the figure) and the second screen accurately depicts the interactive instrumentation in the 2D cockpit. This trainer was created to train intermediate and advanced maintainers within the training continuum, and as such allows for very efficient and timely processes for interaction with the virtual environment and the procedures related to it.

Trainees interact with the virtual aircraft and support equipment using hardcopies or electronic versions of maintenance procedures derived from the IETMs and other sources. The derived procedures include trainer notes where procedural steps may be condensed to streamline operations. The trainer supports limited free-play, allowing actions outside the supported procedures, but within the functional envelope established by the total of all procedures combined.

Figure 5. F/A-18E IVEMT

In this example, the removal of the OBOGS Concentrator is highlighted. The process to interact with the training procedure is very simple and straight forward as shown in Table 4 above. For the purposes of this analysis it is assumed that any preconditions to the training task have already been accomplished, such as making the aircraft safe for maintenance, removal of electrical and hydraulic power, etc. Over five (5) attempts, the removal of the OBOGS Concentrator took an average of six (6) seconds to complete.

CH-147 Chinook Maintenance Trainer (CMT) Interactive Display System (IDS)

The CMT IDS is designed as a dual screen trainer where the trainee(s) can view and interact with the virtual aircraft, virtual cockpit, or animated schematics on each of the two screens. The IDS uses two large (60”) screens at the front of a classroom with trainee interaction using a mouse and touch screen. The IDS is designed to primarily support team training such that two trainees can interact within the same training scenario with both interfaced to a single instance of the simulation software. As an example, team training allows one trainee to start the engine from within the virtual cockpit, while the second trainee stands outside the aircraft looking for smoke emanating from the engines.

Like the F/A-18E IVEMT, this trainer provides excellent training for intermediate and advanced maintainers within the training continuum, but also has a higher level of detail that supports training some initial platform-specific skills. The trainees follow the maintenance procedure using hardcopies of aircraft maintenance manuals as they would during actual aircraft maintenance.

In this example, the removal of the Ramp Control Valve is highlighted (see Figure 6). The process to perform this training procedure, while simple and straight forward, is more complex than the previous example with the F/A-18E, as shown in Table 4. Again, for the purposes of this analysis it is assumed that any preconditions have already been accomplished. The trainee is required to individually remove all eight of the hydraulic connector valves, and the cable harness, while the tagging procedure happens automatically in accordance with the trainer specification. There is no regard as to the order in which the steps are completed in the procedure, rather this functions as it would in the real world based on the physical constraints. As the trainee removes the bolts, there is one action to remove all three, a time saving strategy to maximize training time and reduce trainee boredom or redundant tasks with limited training value. Over five (5) attempts, this process took an average of one (1) minute and fourteen (14) seconds to complete.

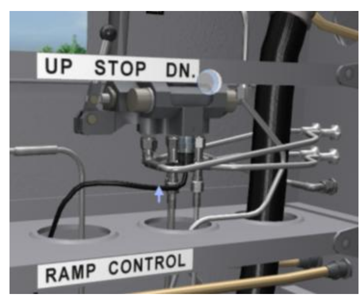

Figure 6. Ramp Control Valve

F-35 JSF Aircraft Systems Maintenance Trainer (ASMT)

The F-35 ASMT provides training of the entire F-35 maintenance process, including analyzing a reported problem, checking out and staging tools and consumables, using the support and test equipment in troubleshooting the problem to a failed LRU, removing and replacing the failed LRU, and checking parts and tools back in. While already in service, development of the ASMT continues as more procedures are rolled out for the Short Take-off and Vertical Landing (STOVL), Conventional Take-off and Landing (CTOL), and Carrier Variant (CV) variants concurrently with aircraft development. Figure 7, a view of the F-35 ASMT’s virtual displays, shows an inspection screen on the left side of the trainer and the 3D virtual environment on the right side of the screen.

Figure 7. F-35 ASMT

This program has a very different set of requirements than the previously discussed programs. The goal for the F-35 ASMT, being a new aircraft that is not widely fielded, is to train maintainers at all levels, including platform-specific initial, intermediate, and advanced levels within the training continuum. As such, this trainer requires the maintainer to check out the required tools for a procedure, bring them to a staging area and inspect them, then introduce them to the scene. This trainer also requires the trainee to remove component pieces, such as lock wire, cotter pins, nuts, washers and bolts individually in the correct order to accomplish removal and installation tasks. This trainer provides trainees with the knowledge to develop an understanding of the basic maintenance tasks and skills to perform the appropriate procedures for the F-35 maintenance activities.

In this example, the removal of the Drag Brace Actuator is highlighted. The process to interact with the training procedure is significantly more complex than the previous two examples, as shown in Table 3 above. For the F-35, the maintainer is required to go to the Depot (Resource View) to check out the appropriate tool, carry it into the 3D environment, and place it in the proper location in order to use it. Also, all of the physical constraints have to occur in a specific order. Cables need to be removed individually and capped, and nuts, washers and bolts need to be bagged and tagged appropriately. Depending on the stage in a trainee's development, the Instructor has the ability to allow free-play operation, or cause a specific scenario to be followed step-by-step. Over five (5) attempts, this process took an average of three (3) minutes and six (6) seconds to complete.

Results Analysis

The F/A-18E IVEMT accomplished the removal of the OBOGS Concentrator in just two (2) steps, the CH-147 CMT IDS accomplished the removal of the Ramp Control Valve in twelve (12) steps, and the F-35 ASMT accomplished the removal of the Actuator from the Drag Brace in twenty one (21) steps. The differences are not the result of variations in aircraft/LRU complexity, since all selected LRUs have comparable parts counts. Instead, the differences are driven by training objectives, device specifications, and the qualifications of the trainee to be taught by that specific VMT as represented within the training continuum.

While the difference in the amount of time taken to complete each removal task (set of tasks) appears to be minimal, it must be noted that these removals are one small segment of a procedure in each of the different VMT programs. The F/A-18E IVEMT was delivered with over 450 procedures, the CH-147 CMT IDS had over 460 procedures, and the F-35 ASMT had over 420. Extrapolating the number of procedures and sub-procedures produces a significant potential impact in the time it takes for a given trainee to accomplish all the required removal tasks when multiplied by the differences in time to accomplish steps based on the differing level of detail.

Training Across the Continuum

While all three programs are excellent examples of training capabilities, they all possess very different features within the entire AMT training continuum. The F/A-18E IVEMT exemplifies a high level AMT for advanced maintainers. At the more advanced levels, a maintainer does not typically need to be reminded of how to use a wrench or a screwdriver; therefore the number of steps you see in the removal of the OBOGS concentrator is minimized in an effort to save valuable training time yet still provide the appropriate training value to the trainee.

At the other end of the spectrum, the F-35 ASMT illustrates a very detailed example of a VMT which can serve for beginning maintainers that need to understand what tools to use, where to get them, how they work and where in or on the aircraft they are utilized, as well as experienced maintainers.

LESSONS LEARNED

Over-specifying the scope and level of detail can lead to higher cost and less than satisfactory overall results in the long term. In the authors' experience, numerous customers have provided feedback indicating, that due to the training exercise time associated with a very high level of detail, generally associated with separately implementing detailed repetitive steps that may not add much training value, training exercises are taking too long to fit within short training schedules.

A specific training course is a training continuum in itself, with differing VMT requirements at the beginning of a course than may exist at the end of a course. As an example, at the beginning of a course it may be appropriate for a student to navigate manually around the 3D aircraft, learn to use common hand tools, interact with individual fasteners, or remove and install items such as nuts, washers, bolts, and cotter pins individually. As the training course continues, however, the VMT needs be able to adapt to the trainee's evolving capabilities, such as supporting auto-navigation aids and grouped removal/installation animations to streamline operation.

Higher level of detail does not always guarantee better training. As experienced by the authors, implementation of ever-higher levels of detail is often only a hedge against an assumption that any deviation from perfection qualifies as negative training. This can drive cost far above the minimum required to achieve the training objective.

Customers need to make informed decisions about the availability of free-play capability versus a procedure-based simulation approach. If the Customer's maintenance concept is "just follow the written procedure," simulation development cost may be reduced by constraining the simulation to just accomplish the procedures' steps, versus allowing the student to go off-procedure. While the use of free-play capability may offer training advantages, particularly in use during instructor non-procedural demonstrations, the ISD professionals must assess the potential advantages versus cost.

CONCLUSION

Technical limitations of the past have been alleviated to the point that fidelity and performance of VMTs are no longer the serious issues they once were. Now, ISD professionals have a much wider VMT capability range to work with in developing the right blended training solution for aircraft maintenance trainers. The wider range of capability, however brings with it the need to tailor VMT requirements to cost effectively match the training objectives and trainee qualifications at the beginning of, and throughout the training continuum. Typical cost drivers in the development of VMTs include the number of maintenance procedures (driven by training objective), level of detail (driven by trainee qualifications), visual fidelity, and subjective requirements to support free-play operation. In addition to cost impacts associated with level of detail requirements, increased level of detail can also impact the time it takes to train specific procedures, and possibly limit the number of procedures that can be trained in a fixed training course schedule.

Lessons learned from fielded systems include the high cost and operational impacts (time to train) associated with over-specification of the level of detail, the need for adaptive HMI approaches in a VMT as a trainee progresses though the maintenance training course, matching graphics fidelity to the training task, and use of a limited free-play capability as a balanced approach to training execution.

As highlighted in the VMT effectiveness study discussed earlier in this paper, (Duke, Bahlis, and Morrissey, 2008), it is proven that VMTs can significantly reduce the development and maintenance costs of aviation maintenance training. However, requirements developers must still balance the wide range of VMT capabilities and implementation approaches, against the cost of those approaches in relation to the training value. In short, just because a technology can be added to a VMT contract, does not mean that it should be.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Mr. Lawrence "Rick" Wrenn, CH-147 IDS Program Manager, and Mr. Donald Lilly, F-35 ASMT Project Engineer, both of the DiSTI Corporation, for their support in development of this paper.

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