E-CATS: First time demonstration of embedded training in a combat aircraft

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Abstract

Air Forces are facing difficulties in training pilots effectively for their missions. Due to a reduction of defense budgets, fewer resources can be made available for training. In addition, airspace available for training is limited, especially in Europe, and this is aggravated by the increase in the range of advanced weapon systems. Moreover, only few Surface-to-Air Missile (SAM) sites are available for suitable training.

Embedded Training (ET) is considered to be a potential solution for these problems. ET for fighter aircraft is a capability installed in an operational fighter to train the pilot while operating the aircraft in a situation it was designed for, but which is not available in everyday life. Thereto, the ET capability generates simulated threats and feeds them into the various avionics systems of the aircraft. This allows pilots to train against a virtual force, or a virtually augmented real force. Benefits of employing ET include cost reduction (fewer real aircraft are needed to act as enemy), use of smaller training airspace (simulated threats may move outside this space), and the potential to train anywhere, at any time.

NLR, Dutch Space, and the Royal Netherlands Air Force (RNLAF) have jointly developed an ET system to demonstrate the feasibility of current technology for implementing an ET capability in fighter aircraft. The system, installed in an RNLAF F-16B, supports training for ground-to-air and (one-versus-two) air-to-air engagements. It consists of two units; one unit executes the ET simulations and provides most of the required interfaces with aircraft systems, while the other unit is dedicated to interfacing with the radar processing chain.

The system was evaluated by demonstrating it to a group of pilots and engineers and collecting their expert opinions. It was concluded that embedded training has considerable value for a variety of training objectives related to Beyond Visual Range tactics, and it is expected that embedded training will play an important role in the future mission training of fighter-aircraft pilots.

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1. Introduction

Embedded training is frequently claimed to be the solution for the problems that Air Forces are facing in training pilots for their missions. As a result of decreasing defense budgets, it is becoming increasingly difficult to allocate the appropriate training resources (e.g., fighter aircraft acting as enemies and range instrumentation systems). Due to environmental concerns, there is a pressure to reduce training airspace. This problem is aggravated by the increase in range of advanced weapon systems.

Also, the emerging network-centric warfare concept in which information networks link sensor, command, and engagement facilities, imposes logistics challenges for mission training. The purpose of this article is to introduce the concept of embedded training in fighter aircraft, to present the design of the prototype system installed in the two-seat F-16B MLU (Mid-Life Update) with tail number J-655, and to discuss the results of the demonstration flights conducted with the system. This introduction continues with a brief description of embedded training, its advantages, and its development history within the Netherlands.

Embedded Training (ET) can be defined in general as a built-in capability of an operational system that enables the operator to use the system in a situation where it was designed for, while that situation is not actually available. More specifically for fighter aircraft, ET allows pilots to train intensively and real-
istically by immersing them into a mission scenario augmented with synthetic (or virtual) entities with which they can interact (Fig. 1). As a result, the pilot is able to utilize his aircraft (“ownship”) to its full capability and to engage large numbers of air and ground threats in challenging scenarios.  

The pilot interacts with the virtual threats by using his (unmodified) cockpit controls and displays. For example, he may perform identification, fire weapons, and apply countermeasures. Effectiveness of countermeasures is also realistically simulated. Virtual threats will show a realistic intelligent behavior. For example, they fire missiles at the real aircraft and apply countermeasures when they are attacked. As a result, ET comes as close as possible to real combat missions.

Application of ET gives rise to several direct advantages [4]:

1. A first advantage is cost reduction. In live combat training without ET, real aircraft act as the enemy. These so-called ‘red air’ flights are costly and obviously provide only limited training value for the pilots flying them. With budgetary constraints on flight hours, ET as a mere ‘red air replacement’ will be very cost effective.  

2. A second advantage is that a relatively small volume of airspace is needed. Many of today’s and future air-to-air engagements are Beyond Visual Range (BVR). Detection of the enemy, identification, weapon delivery, and electronic warfare all take place at relatively long distances between the players. In live combat training of BVR engagement, training areas are needed as large as 100 × 100 nautical miles (NM). With ET, however, only small areas are needed, simply because only space for the real aircraft is required. Since airspace for military training is scarce, particularly in Europe, ET will give significant logistics advantages.

3. Another advantage is realistic simulation of ground threats. In current tactical combat training, participation of realistic ground threats, such as Surface-to-Air Missiles (SAMs), is expensive and sometimes technically not feasible. ET technology, however, has the potential of realistic simulation of ground threats. Moreover, ground threats can be replicated as many times as needed and can be positioned at any location, even at sea.

4. ET offers flexible simulation of air threats. Virtual, as opposed to real red-air aircraft, can be given any characteristic, thereby increasing the number of possible training scenarios.

5. There is also a security benefit. Since the red-air flights are virtual flights, a less friendly observer is not able to deduce the whole tactics picture by watching the training effort.

Other benefits of ET include, real-time feedback to the pilot (‘wounded’, ‘killed’, etc.) and convenient post-flight evaluation of training results.

The history of the development of ET technology for fighter aircraft at the National Aerospace Laboratory NLR dates back to the mid-1990s when NLR and Dutch Space participated in a European long-term strategic defense program (EUCLID) to assess the feasibility of ET for fighter aircraft. The outcome of this study formed the basis for further development of an ET system, which was demonstrated in July 2003 on the AerMacchi MB 339 trainer aircraft. This aircraft is not equipped with a mission system. Therefore, the addition of the ET system required limited integration with existing on-board systems [8]. In the meantime, in a national Netherlands program, NLR and Dutch Space designed and implemented a software-based ET module on an F-16 MLU flight simulator, which has been demonstrated in August 2000. It proved the concept of ET and identified the benefits for operational use. In June 2003, NLR, Dutch Space, and the Royal Netherlands Air Force began a joint effort to develop an ET demonstration system, to install it in an F-16 combat aircraft, and to execute a flight program for demonstrating embedded training capabilities. This ET demonstration system was named E-CATS, which stands for Embedded Combat Aircraft Training System. The main objectives of the project were to demonstrate the maturity of the Dutch ET technology and to gain insight in the integration of ET with the mission system of an operational fighter aircraft, e.g., an F-16. Fig. 2 in-
indicates how the maturity of the Dutch ET technology has been gradually advanced.²

Section 2 of this article presents an overview of the general ET concept for fighter aircraft. Next, Section 3 addresses the requirements imposed on E-CATS, including the operational scenarios to be supported, system limitations, and development constraints. Section 4 presents the system design, while the activities for the verification and validation of the simulation models are described in Section 5. A typical training mission with E-CATS is described in Section 6. Section 7 reports how the system has been evaluated. Finally, Section 8 offers some conclusions.

2. General ET concept for fighter aircraft

2.1. Functional architecture

An ET system consists of an airborne segment and a ground segment (Fig. 3). The airborne segment has two main simulation modules: the Ownship Simulation module and the Virtual World Simulation module. The Ownship Simulation module simulates the on-board sensors and simulates the own weapons and electronic warfare systems. The Virtual World Simulation module simulates the virtual entities in the training exercise.

The Simulation Management module controls the overall course of the training exercise. It allows the pilot to select, start, and stop training scenarios that have been prepared beforehand on the ground with the Scenario Generation facility. A specific safeguarding function ensures the safety of the aircraft by automatically stopping the training exercise when a safety risk occurs. While a training exercise is in progress, the Data & Audio Recording module gathers all the data that are needed for after-action review using the Debriefing facility.

This basic architecture is sufficient for the training of engagements in which one ET-carrying aircraft is involved and all other players are simulated. However, in more complex and realistic exercises, with more than one training aircraft taking part, a Simulation Data Link between ET-carrying aircraft is needed to ensure that all players have matching virtual world information.³

2.2. Airborne segment

The Ownship Simulation includes models of the aircraft systems that are relevant for ET. Displays and controls for e.g., the radar, the radar-warning receiver, and the air-to-air interrogator for friend/foe identification must interact as if real threats are present. Because weapon delivery must also be simulated, Ownship Simulation includes models for fire control, the weapons loaded, on-board guns, dispensers (chaff and flares), and the electronic warfare system. The Ownship Simulation module maintains an intensive two-way communication with the aircraft’s mission system. The mission system handles sensor data, weapon data, and electronic warfare data. Each time the pilot gives an input to one of the cockpit systems, the simulation is updated and the resulting new simulation data are fed into the mission system. Another part of the Ownship Simulation is a realistic assessment of damages to the ownship resulting from deployment of virtual weapon by opponents.

The Virtual World Simulation includes models of the ground threats and air threats, their electronic signatures, weapons, and dynamic behavior, involving strategies, tactics, maneuvers, and countermeasures. Moreover, the behavior of the virtual entities has to be in exact accordance with their individual roles (ground-based or airborne, friend or foe, fighter or fighter-bomber, etc.). Virtual world simulation may also comprise models for the terrain over which the exercise takes place and for the atmospheric conditions.

Ground Control Intercept (GCI) can also be provided as part of the virtual world. A simulated GCI is particularly useful during ET exercises when no data link facility is available to transfer the virtual world to the ground-based real GCI. In its simplest form, the virtual GCI provides aurally an air picture to the pilot. To be realistic, however, the virtual GCI should be able to interact with the pilot and conduct some form of tactical control.

During the exercise, the Simulation Management module controls all simulations. In addition, this module controls the recording of the exercise and measurement of the pilot’s performance. Performance aspects include use of weapons, sensors, and countermeasures, selection of tactics, maintaining planned mission routes, and selection of opponents.

In case of severe safety risks, the safeguarding function automatically shuts down the execution of the training scenario to allow all pilots to regain situational awareness of the real world. Potential safety risks are, for example, the inadvertent crossing of the boundaries of the reserved airspace by pilots immersed in ET or a virtual target flying through mountains and thereby putting the training pilot in danger. A similar safety risk occurs

² These maturity levels are applied by the JSF Science and Technology Advisory Board (JSTAB), which was established by the JSF Program Office to guide the program’s long term science and technology strategy.

³ More generally, an air-to-ground data link will also be needed to integrate ground-based entities, such as an Instructor Operation Station (IOS) and ground-based fighter aircraft simulators, in the ET exercise.
in the case of real problems, for example due to a system failure, low fuel, or a severe low speed situation when the pilot needs all his attention to keep control of the aircraft.

2.3. Ground segment

By means of the Scenario Generation module, the individual scenarios can be prepared, and scenarios can be selected to compose a combined set for the planned training exercise. After verification of the scenarios, the digital representation of the set of scenarios can be loaded in the ET-carrying aircraft, e.g., by physically inserting a memory cartridge into the system or by data link.

The Debriefing module is used for post-flight review and evaluation purposes. It provides the pilot and his instructor with an interactive tool for replay of in-flight recorded data that produces a synchronized presentation of the on-board displays, the 3-D trajectories of all entities (e.g., aircraft, missiles), and a list of events that occurred during the training exercise (e.g., missile launch, chaff deployment).

3. E-CATS requirements, limitations, and development constraints

In the previous section, a general description of the ET concept for combat aircraft has been given. In this and subsequent sections, the focus is on E-CATS (Embedded Combat Aircraft Training System), a prototype system for demonstrating the potential of ET in an F-16 aircraft. It is not possible to present in this article the complete set of requirements imposed on E-CATS [12]. Here, the operational scenarios to be supported are described, as well as the most important system limitations and development constraints that E-CATS has to comply with.

3.1. Operational scenarios

E-CATS has to support two operational scenario types: a ground-to-air scenario and an air-to-air scenario. These two scenario types may be trained in combination as well.

For composing a ground-to-air scenario, two types of Surface-to-Air Missile (SAM) sites are available. These are the Russian SA-6 and SA-10, which can be positioned at arbitrary locations. These ground threats search, detect, track, and fire missiles at the ownship. The ownship Radar Warning Receiver (RWR) gives audio search indications, as well as track and launch indications. Threats are displayed by an appropriate symbol on the RWR Azimuth Indicator. The position of the symbol indicates the location of the threat with respect to the ownship. Defensive actions, such as beaming and deployment of chaff may result in break-lock of the SAM’s radar, and then the RWR indication will stop. The missile closest point of approach is computed and the ownship damage will be determined using concentric rings of probability-of-kill. The most inner circle will result in a kill notification, the middle ring in a wound notification, and outside these rings means survival.

An air-to-air scenario consists of a hostile two-ship (Russian SU-27 Flankers) and a friendly two-ship that returns to base (RTB). Ground Control Intercept (GCI) gives verbally an air picture in Bearing Range Altitude (BRA) format with respect to a predefined position (“bullseye”). GCI calls are made once per minute. When an entity is within 15 NM of the ownship, no further GCI calls are made for that entity. A virtual entity will appear on the radar display if the radar set-up covers its position, and if the entity is within detection range. The hostile two-ship will deploy long range missiles (AA-10C Alamos). Just as for ground threats, the RWR will provide indications for the air threats. The use of beaming and chaff may again

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4 Beaming is the action of flying perpendicular to the direction of the radar beam. Pulse-Doppler radar has difficulties tracking targets under this condition.
result in break-lock. The impact of incoming missiles is determined likewise as for the ground-to-air scenario. The ownership can eliminate hostile aircraft by firing simulated missiles. In this case only two damage results are possible: kill or miss.

3.2. System limitations

Due to restricted development time, limited budget, and technological difficulties, several limitations were accepted for the functions provided by E-CATS:

1. Air-to-ground scenarios in which ground targets need to be eliminated by using precision weapons will not be supported.
2. Embedded training scenarios with only one ET-equipped aircraft (“single-ship”) will be supported. Consequently, there is no need for the development of a simulation data link facility (see Fig. 3).
3. Virtual entities and real entities will not be mixed on the radar display. While no simulation is running, the radar display shows real entities. After a simulation is started, only virtual entities are shown.
4. No identification interrogation will be provided for virtual entities. Consequently, threat identification will have to be provided by the GCI calls.
5. Interactive communication between pilot and GCI will not be supported, since this would require speech recognition capabilities. GCI will only make periodic calls giving the location, heading, and identity of each group of virtual entities.
6. Within Visual Range (VVR) engagements will not be supported. ET VVR engagements require that a visual image of virtual opponents can be superimposed on the outside world as seen by the pilot. Helmet Mounted Displays or other displays suitable for realistic visualization of virtual opponents in the outside world do not yet exist.

3.3. Development constraints

Since E-CATS will be an experimental system to be installed in an F-16 aircraft for a limited period of time, some specific constraints governed its development:

1. All aircraft systems have to remain operational. For example, none of the systems should have to be removed from the aircraft to obtain installation space.
2. Without E-CATS installed, all aircraft systems should function normally. That is, the (wiring) modifications required for E-CATS should not have any impact on the operation of the aircraft. Also, when E-CATS is installed and its power is switched off, all aircraft systems should function normally.5
3. After completion of the E-CATS flight demonstration program, it should be possible to bring the aircraft back to its original state, as if no modifications were ever made. This constraint implies that it is not allowed to cut any of the existing aircraft wiring, but that existing (unused) cables, free (test) connector pins, and new cables have to be used.

4. E-CATS design

The E-CATS design has been derived from the general ET functional architecture (Section 2), taking the specific E-CATS requirements, limitations, and constraints (Section 3) into account. This description of the E-CATS design focuses on the major innovation of the project, i.e., integration with the mission system of the F-16 MLU aircraft. Refer to [9,11] for details on the system design.

4.1. System architecture

The hardware architecture for E-CATS is depicted in Fig. 4; only the aircraft systems and connections relevant to E-CATS are shown. The Modular Mission Computer (MMC) is the heart of the mission system. It acts as primary bus controller for a set of dual redundant MIL-STD-1553B buses; these, in particular the C-MUX and D-MUX are relevant for E-CATS. The units shown in the top row of the figure are part of the pilot vehicle interface. The two grey blocks represent the units that together form E-CATS, i.e., the Embedded Training Computer System (ETCS) and the Embedded Training Radar Gateway (ETRG). To exchange information, these two units are connected by means of an Ethernet link.

The ETCS is a PowerPC-based platform running an Embedded Linux operating system and the EuroSim simulation engine [6]. The ETCS is installed in the centerline pylon mounted directly under the aircraft. The execution of all embedded training simulation software takes place in the ETCS.

The ETRG is also a PowerPC-based platform, but it runs the VxWorks real-time operating system. The ETRG is installed in the tray designated for the future installation of a Helmet Mounted Display interface unit (aft avionics compartment). The main function of the ETRG is to inject radar observations of virtual entities into the mission system. It breaks into the connection between the Fire Control Radar (FCR) and the D-MUX bus (“break-in” mode). When the ETRG power is switched off, or when no simulation is running, it reconnects the FCR with the D-MUX bus directly (“transparent” mode). When the E-CATS units are removed from the aircraft, the ETRG is replaced by a “Dummy-ETRG” that wires the FCR to the D-MUX bus for normal operation.6

Fig. 5 shows the architecture of the simulation software executed by the ETCS. It consists of a set of modules grouped

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5 This latter constraint has actually been specified as a safety requirement in [12].

6 The ETCS does not break into any connection; it only attaches to existing connections and unused inputs. Hence, no special measures need to be taken to restore normal aircraft operation when it is removed.
around the Tactical Environment Data Pool (TEDP). The TEDP stores information related to all entities, events, and emitters. Examples of entities are aircraft, missiles, and SAM-sites. Events include chaff deployment, missile release, and missile detonation. Emitters are the radar systems of aircraft and SAM-sites. Emitters are always associated with an entity. Some modules, e.g., radar model and GCI model, only monitor objects in the TEDP, while other modules, e.g., SAM-site model and aircraft model, monitor as well as update objects in the TEDP. The simulation management module obtains information from the TEDP related to safeguarding (e.g., ownship position) and simulation control (e.g., ownship’s killed status). The sound-generator module is a facility that can be triggered by other modules to play specified audio samples.

4.2. Integration with Fire Control Radar

The Fire Control Radar (FCR) is the primary target detection and tracking sensor of the F-16. The FCR processes the radar signals returned by targets (echoes) and presents the pilot with a synthetically generated image made up of a set of predefined symbols. The pilot may select different radar operating modes by using either the throttle, the sidestick, or the radar control panel [1]. The integration of E-CATS with the radar processing chain is based on the use of the Track While Scan (TWS) mode of the FCR. In this mode, the FCR transmits up to 10 target observations (“track” targets) in message blocks via the D-MUX bus to the Multi Function Display System (MFDS) and the Modular Mission Computer (MMC). As shown in Fig. 6, the ETRG breaks into the original connection from the FCR to the MFDS and the MMC.\footnote{The implemented solution does not support visualization of virtual “search” targets. Search targets are contained in a video signal that is generated by the FCR and superimposed on the radar display of the MFDS.}

As can be seen from Fig. 6, the ETRG operates as a switch with two states, controlled by the ETCS. When no simulation is running, it connects the FCR (through the D-MUX bus) with the MFDS/MMC, and observations of real objects are displayed on
When a simulation is running, the ETRG connects a model of the radar system (executed by the ETCS) with the MFDS/MMC, and observations of virtual objects are displayed on the MFDS. As a result, it is not possible to mix real-world observations with virtual-world observations. This is acceptable, because E-CATS supports only single-ship operation, and the ownship is the only real aircraft present in the training area during an ET exercise.

### 4.3. Integration with Radar Warning Receiver

The Radar Warning Receiver (RWR) monitors the radar environment to alert the pilot of any hostile or foreign activity that may be taking place. When it receives a radar signal, it matches that signal with its set of known signals and displays a graphical symbol representing the type of radar and its relative location on the RWR Azimuth Indicator. If the system determines that the radar is an immediate threat, it will give a distinctive audible warning. For ET purposes, the RWR is loaded with a special software version that is capable of receiving externally generated threat symbols from the EW-MUX bus for display on the RWR Azimuth Indicator (refer to Fig. 4). A model of the RWR (executed by the ETCS) determines the symbols to be displayed and their positions on the display depending on the radar activity of the virtual entities (air threats, as well as ground threats). This information is fed to the RWR (Fig. 7). The symbols associated with virtual entities are superimposed on the symbols generated for real entities.

Since the RWR generates search and track audio cues directly from the received radar signals, such audio cues cannot be generated for virtual entities. The solution has been to store digital samples of relevant audio cues in the ETCS, and to play these sounds on the pilot’s headset when appropriate.

### 4.4. Integration with weapons and countermeasures

The pilot can deploy missiles to eliminate hostile aircraft. The MMC transmits message blocks over the D-MUX bus containing an indication of missile launch and other relevant parameters associated with it, such as the weapon identification. The ETRG continuously monitors these message blocks and forwards them to the ETCS. The ‘missile-launched’ indication is used to trigger the execution of the missile model within the virtual world simulation (executed by the ETCS).

The pilot can dispense virtual chaff as a countermeasure to incoming virtual missiles. Of the buttons available to the pilot for dispensing chaff, the bump switch is wired to the ETCS. The ETCS executes a model of the chaff-dispensing unit, which maintains a count of the remaining amount of chaff. When the pilot hits the switch, an applicable audio message is played on his headset, i.e., “chaff/flare” (if sufficient chaff is available), “low” (if the amount of chaff is less than 25% of the initial amount), or “out” (if there is no more chaff available). The missile models executed by the ETCS evaluate whether dispensed chaff will lead to a radar break-lock or not.

### 4.5. E-CATS control

During flight, embedded training scenarios need to be selected, started, and stopped. A specific page that can be called up on any one of the two MFDS displays is used to control E-CATS.11 The layout of the E-CATS control page is shown in Fig. 8.

Of the twenty Option Select Buttons (OSBs), mounted in the bezel of the display, OSBs 6-10 and 18-20 are used for E-CATS control. Four-character labels can be displayed near each OSB. A label will only be displayed if the associated OSB is active. The labels displayed at OSBs 6-10 represent up to five choices for embedded training scenarios. The labels RUN, STOP, and CLR can be displayed at OSB 20, 18, and 19, respectively, to start and stop simulations, or to cancel a selection. The central area of the display consists of three fields. The ‘Simulation state’ field is used to display the system state, e.g., “E-CATS: RUNNING”. The ‘Scenario description’ field gives a one-line

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8 General flight safety requirements do not impose that the FCR should be operational while embedded training is taking place.

9 The use of virtual flares as a countermeasure has not been implemented, since heat-seeking missiles are not simulated.

10 The remaining virtual chaff count is not communicated to the Electronic Warfare Management Unit (EWMU). Hence, the available chaff indicated on the EW Prime Indicator will not reflect the amount of virtual chaff available.

11 The “recce-test” page for controlling a reconnaissance pod mounted under the centerline pylon has been used to implement the E-CATS control page.
description of the selected scenario, e.g., “SCN3: TWO BOGIES.” The ‘Message area’ field gives further relevant information, e.g., why the simulation has stopped (e.g., “STOPPED BY PILOT”). Changes in the simulation state are accompanied by voice messages on the pilot’s headset.

Fig. 9 depicts the flow of control information. The ETCS transmits a message block on the C-MUX bus that contains the 4-character labels for each OSB. The MMC relays the message block to the D-MUX bus. The MFDS receives the message block and places the labels at the appropriate locations on the display. The ETCS also produces a video overlay for the central area of the display (‘Simulation state’, ‘Scenario description’, and ‘Message area’ fields). The video signal is connected to an input of the Display Generator, which connects the signal to the MFDS display that shows the E-CATS control page. The MFDS transmits a message block on the D-MUX bus that identifies OSB depressions by the pilot. The MMC relays the message block to the C-MUX bus. The ETCS receives this message block and processes it accordingly.

5. Verification and validation of simulation models

Verification and validation has been an integral process of the E-CATS development. Here, we define verification as confirmation by examination that the system and its units fulfill the specified requirements, and validation is defined as confirmation by examination that the end product fulfills its intended use when placed in its intended usage environment. Four levels have been distinguished in the verification and validation process, i.e., unit testing, system lab-testing, system ground-testing, and system flight-testing. The first three levels can be classified as verification, while the fourth level is considered validation. This article is limited to a description of the testing activities that have been carried out for the software modules that simulate virtual world entities (aircraft, missiles, and SAM-sites).

5.1. Unit testing

Unit testing takes place at the workstation of the software developer. Use is made of a test harness that produces input data needed by the unit under test and presents the output data of the unit under test for verification purposes. Exchange of data between the test harness and the unit under test takes place via shared memory that is representative for the Tactical Environment Data Pool (TEDP). The configuration for unit testing is depicted in Fig. 10.

In this way, for the aircraft model, the flight paths are verified for the different flight phases, i.e., en-route, presentation, pre-emptive maneuver, and engagement. The trajectories of missiles launched by hostile aircraft are also verified. For the SAM-site model, the ranges for tracking, firing, maximum altitude, etc. are verified, as well as the trajectories of launched missiles.

5.2. System lab-testing

System lab-testing is performed at a laboratory set-up of E-CATS. The environment of the E-CATS units (see Fig. 4) is created by using a mix of real subsystems (e.g., RWR and RWR Azimuth Indicator) and simulated subsystems (e.g., FCR, INS)[5]. The EuroSim simulation tool [6] provides facilities for monitoring the behavior of entities in the TEDP; the information is presented in numerical format. In addition, a 3-D Stealth display application is used to generate a top view of a scene showing all entities overlaid on a geographical map. Using these facilities, static tests in which the ownship remains stationary are performed to verify the combined behavior of all software models, including the calls made by the GCI model.

5.3. System ground-testing

System ground-testing takes place in a shelter at the air base with E-CATS installed in the F-16 aircraft [5]. Compared with system lab-testing, the real environment of E-CATS is now present. As in system lab-testing, EuroSim is used to monitor the behavior of the entities in the TEDP. The main purpose of system ground-testing is to make a final checkout before system flight-tests. A limited set of static tests is performed to check that the E-CATS functions are operational. For some of these tests, a pitot tester is used to simulate that the F-16 aircraft is at the desired flight level.

5.4. System flight-testing

System flight-testing consists of executing actual flights with E-CATS installed and conducting embedded training sessions [5]. During a flight, E-CATS records the behavior of all the entities in the TEDP. In addition, video recordings are made of the two displays of the MFDS and the Head Up Display (HUD). After flight, the video and data recordings are analyzed to decide on (further) fine-tuning of model behavior. The expert

12 This 3-D Stealth display application is also used in the debriefing system (see Section 6.3).
opinion of the pilot(s) is thereby taken into account. After every software revision, regression tests are performed at the four levels of verification and validation. This process is repeated until the system is ready for the demonstration flights.

6. E-CATS training mission

A training mission with E-CATS consists of three phases: mission preparation, mission execution, and mission evaluation (Fig. 11). The activities in these phases are described in more detail in the following subsections.

6.1. Mission preparation

From the pilot’s point of view, preparation for an E-CATS training mission will be the same as for any normal mission. Using existing mission planning systems, input data like target data, intelligence data, and meteorological data are analyzed and transformed into data for use on-board, like way points, weapon load, expected threats, etc.

E-CATS training missions require an additional step, i.e., the preparation of data that define the virtual situation to occur during execution of the training mission (the training scenario). This is an instructor function. It involves definition of parameters for virtual entities, including locations of SAM-sites and types, routes and tactics followed by hostile aircraft, and routes of friendly aircraft. Also the training area and the scenario entry conditions need to be specified. Fig. 12 shows an example of a scenario that contains a combination of ground and air threats. Inside the box, some safety levels and scenario starting conditions are specified. The SA-6 is activated three minutes after the start of the scenario. Also note that the SA-10 is located outside the training area. A PC-based scenario generation tool has been developed that is built on the commercially available tool Falconview [3].

6.2. Mission execution

Upon arrival at the designated training area, the pilot can select one of the available scenarios. Only after all safety conditions and scenario entry conditions are satisfied, as announced by a voice message (“System stand-by”), the pilot can start the ET scenario. An example of a safety condition is that the aircraft should be inside the training area. An example of a starting condition is that the heading of the aircraft should be west. After starting the scenario, the pilot will be confronted with the
6.3. Mission evaluation

To support debriefing of E-CATS training missions, a PC-based debriefing system has been developed. Fig. 13 shows the set-up of the video screens used for debriefing. The left screen shows the combined video recordings of the left and right MFDS displays and the Head Up Display (HUD). These recordings are made as normal practice during every mission. The right screen shows a top view of the training scene as it is generated by replay of the recorded data. It is generated by a specific 3-D Stealth display application. Replay can be performed at speeds up to $5 \times$ real-time. The center screen shows a list of events that occurred during the training mission, such as start and stop of simulation runs, deployment of countermeasures, missile launches, and kills. The event list supports a fast stepping between events that occurred during the training session. Synchronization between all screens is maintained while using (fast) replay, or stepping from event to event.

7. E-CATS demonstration and evaluation

In the week of 4–8 April 2004, an E-CATS demonstration program was carried out at the airbase Leeuwarden of the Royal Netherlands Air Force. A group of six pilots and six system engineers from both the JSF Program Office (JPO) and Lockheed Martin Aeronautics Company was invited to participate in the event. Three Dutch pilots acted as hosts.

6.3. Mission evaluation

To support debriefing of E-CATS training missions, a PC-based debriefing system has been developed. Fig. 13 shows the set-up of the video screens used for debriefing. The left screen shows the combined video recordings of the left and right MFDS displays and the Head Up Display (HUD). These recordings are made as normal practice during every mission. The right screen shows a top view of the training scene as it is generated by replay of the recorded data. It is generated by a specific 3-D Stealth display application. Replay can be performed at speeds up to $5 \times$ real-time. The center screen shows a list of events that occurred during the training mission, such as start and stop of simulation runs, deployment of countermeasures, missile launches, and kills. The event list supports a fast stepping between events that occurred during the training session. Synchronization between all screens is maintained while using (fast) replay, or stepping from event to event.

7. E-CATS demonstration and evaluation

During the first day, presentations were given about embedded training in general and about the capabilities and limitations of E-CATS. Also, four training scenarios for the demonstration flights were presented:

1. Surface-to-air scenario including an SA-6 and an SA-10 site. This scenario was used to show SAM-site behavior, RWR indications, effect of defensive reactions, effect of countermeasures, and E-CATS safety features.
2. Air-to-air scenario 1 with a hostile two-ship making an “azimuth-split” presentation. This scenario was used to show the radar displays, GCI calls, and virtual threat formations and maneuvers.
3. Air-to-air scenario 2 with a hostile two-ship making a “lead-trail” presentation. This scenario was used to show basic engagement tactics.
4. Combined scenario (see Fig. 12). This scenario was used to highlight all the virtual threat interactions with the aircraft and to demonstrate increased workload.

During the following three days, a total of 8 training missions were executed; each consisting of a briefing, the flight itself, and a debriefing. Each flight took approximately one hour and was flown with a Dutch pilot in the front seat and either a guest pilot or engineer in the back seat. Embedded training was conducted in an area over the North Sea. First, the Dutch pilot demonstrated the system by flying each of the four scenarios. Then, the back seat pilot could fly various combinations of the scenarios for the remainder of the mission.

7.2. Participant feedback

After his flight, each guest pilot provided ratings on the degree of realism, the effectiveness, and the overall training value of training with E-CATS on a 1 to 5 points scale [7]. Concerning the realism (Fig. 14), participants rated enemy behavior, radar system, and weapons systems as very realistic (average > 4). Participants were least positive about the realism of GCI (average 3.4 points). One of the shortcomings of GCI was that it
reported the exact positions of the virtual aircraft, whereas in reality there may be inaccuracies in the GCI reported positions. Nevertheless, they still found the basic GCI feature very useful and preferred it to having no GCI at all.

Concerning the perceived effectiveness and overall training value, the averaged ratings are shown in Fig. 15. Participants were asked to compare the effectiveness of E-CATS to live exercises, as well as to a ground mission simulator for 18 training areas. Training areas with four or fewer responses have been removed, i.e., low observability, team training, and lasers. Largest gain over live training is found for weapons use. Largest gain over simulator training is found for attention management and BVR tactics. E-CATS is considered not very effective for training integrated tactics and (obviously) WVR tactics. Overall training value is considered to be the strongest for attention management, with a high score for weapons use too.

8. Concluding remarks

An embedded training system, E-CATS, was developed that was integrated with the mission system of an RNLAF F-16 MLU aircraft to provide training opportunities in a real aircraft against virtual threats on the ground and in the air. The functionality of E-CATS was limited to single-ship scenarios in BVR situations. To the author’s knowledge, E-CATS has been the first time demonstration of embedded training in an operational combat aircraft, taking into consideration the level of integration with the existing mission system.

From the findings of the pilots and system engineers who participated in the demonstration flights, it can be concluded that embedded training as demonstrated by a relatively simple system as E-CATS has considerable training value for a variety of training objectives related to BVR tactics. It was indicated that E-CATS as it is, would already provide more training value than current live training and ground-based simulator training. The system demonstrated ET potential beyond participants’ expectation on most of the combat experiences supported by the demonstration scenarios. It is expected that embedded training will play an important role in the future training of fighter-aircraft pilots for all types of BVR tactics.

A follow-on project has been started to further increase the maturity of embedded training. Specific further developments are required in the areas that have been identified as current E-CATS limitations, including multi-ship operation, mix of real and virtual entities on the radar display, and integration of Advanced Interrogation Friend or Foe (AIF). Last but not least, there are a number of technological challenges related to these further extensions, including development of a multi-ship sim-
ulation data link and further integration of the hardware components to minimize the required space for installation.

For new aircraft, like the Joint Strike Fighter (JSF), the integration of ET shall have to be taken into account in the aircraft design phase, rather than thinking of ET as an add-on system.

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