USING VIRTUAL REALITY FOR EVIDENCE-BASED TRAINING IN AVIATION LINE OPERATIONS: MOVING FROM ERROR TO UNDESIRED STATE MANAGEMENT

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Abstract

Evidence-based training (EBT) focuses on managing the most relevant threats and errors, based on evidence collected in operations and training, so as to ensure safe, effective and efficient operations in a commercial air transport environment. This enhances the relevance of training content as it is aligned with the actual blend of technical and non-technical skills and knowledge needed.

This paper examines the use of virtual reality for implementing EBT, especially in transiting from error to undesired state management. Mismanaged threats and errors can lead to undesired states that reduce the margins of safety and increase the probability of adverse events. For example if a crew selects a wrong approach and this error was subsequently identified, error management would be attempting to reprogram the correct approach which if untimely could result in an unstable approach. The crew is “locked in” to error management rather than switching to undesired aircraft state management.

Virtual reality can explicitly and realistically simulate threats and errors and their associated undesired states and outcomes. A case study is provided to demonstrate how realistic and immersive 3D interactive content can be an effective EBT for teaching appropriate actions in the phases of error, undesired and outcome.

Introduction

Traditional training in aviation, in addition to being prescriptive about what is the “right”, tends to be normative and didactic in nature and generally has not proven particularly effective particularly for dynamic environment like the aviation workplace, where accidents could arise from many unsuspected sources of vulnerability in situations. During the occurrences of these fundamental surprises (Reason, 1990) and inconceivable events (Lanir, 1989) whether hidden (Westrum,
1982) or incomprehensible (Perrow, 1984), the individual is susceptible to sudden losses of “structural” meaning derived from the training. Instead of asking where should they go, when do they take a stand, or what should their strategy be, they instead face the more frightening feeling that their old “structural” labels are no longer valid. They have outstripped their past experience and are not sure either what was up or who they were. Until they develop some sense of these issues, they just try to find rationality by acting according to their mental models in order to reduce the confusion.

In the 2015 AirAsia crash in Surabaya, investigation showed that there was a need for training on how to react in unsafe situations rather than just knowing what is safe and how to keep safe. It recommended that flight simulators be programmed for these unsafe situations in order to train pilots how to react appropriately. The investigation, a joint effort involving Australian, French, Singaporean and Malaysian authorities, pointed to weaknesses in pilot training in dealing with upsets, or when an aircraft is angled greater than 45 degrees.

"Our recommendation to AirAsia is to train their pilots flying the Airbus plane on how to make an upset recovery. The AirAsia pilots had not been trained for that scenario, he added, because the manual provided by the plane’s manufacturer said the aircraft, an Airbus 320, was designed to prevent it from becoming upset and therefore upset recovery training was unnecessary. A huge amount of training is done on takeoff and landing and traditionally, of course, is 70-80% (of when accidents take place); only 10% takes (place) in the cruise phase of flight. But if something does happen in the cruise phase of flight, it does typically end up fatal."

investigator Nurcahyo Utomo (2017)

This incident highlights the need for training to instead focus on detailing actual error scenarios, identifying how the staff can be primed to recognize their occurrences, and equipping to resolve the errors and finally upon failure of the resolution, what to do as the error escalates into an undesired state management situation. In the undesired state, often the “hard” safeguards (like aircraft design, and include automated systems, instrument displays, and aircraft warning) and
“soft” safeguards (include regulations, standard operating procedures, and checklists to direct pilots and maintain equipment; and licensing standards, checks, and training to maintain proficiency) are already in place. Whether they are used correctly or engaged in the appropriate mode no longer matters. At this point, it is the action scripts of the aviation personnel like flight crew or line staff that can either resolve the undesired state or contribute to its escalation into an accident.

This paper draws from the Threat and Error Management (TEM) research developed as part of the LOSA Collaborative (Merrit & Kinect, 2006) to outline the concepts of error (as opposed to threat) and how undesired state management is different from error management. It then argues that training should focus simultaneously on the operating environment and people working in that environment in order for performance to be in the “natural” or normal operating context. The resulting training outcome will be more realistic, dynamic, and holistic. As the TEM taxonomy can quantify the specifics of the environment and the effectiveness of performance in that environment, the outcomes are highly diagnostic.

The content of the training should not just be based on the specifics of the environment. The environment is the context for how one understands themselves, others, and the situation of a particular moment and these perceptions are dialectically constructed socially and experientially through meanings and understandings. Although there is a low probability of undesired states occurring, the training should make it necessary for each individual to be equipped with knowledge that deals with where they are, what had happened, what is happening, what is changing and what could change. Just on the onset of the accident, the individual often feels like vu jàdè (I have never been here, I have no idea where I am and I have no idea who can help me) and both the sense of what is occurring and the means to rebuild that sense collapse totally. The training must be about how one can quickly reconstitute contextual rationality. This is done by inculcating a sense of déjà vu to help one recognize, interpret, and negotiate unanticipated situations and continuously create and reenact the sense and meaning of the elements in the
The delivery of such highly contextualized and interactive contents in almost real-time perception can only be possible using Virtual Reality (VR) as it had been shown to be an effective mean of enhancing, motivating and stimulating learners’ understanding of certain events, especially those for which the traditional notion of instructional learning have proven inappropriate or difficult (Pan, and et. al., 2006). VR training could be as effective as compared to real life training (Andreatta, et. al. 2010) as the virtual experiences enable users to begin to visualize and recognize complex workplace situations, build up knowledge of procedures and skills, and undergo training in a safe and forgiving environment. Not only does the technology allow participants to interact with an immersive program highly responsive to movement through space, it contains the potential for presenting trainees with situations in which they can manipulate objects and engage with artificial intelligence.

**Evidence-Based Context for Training**

Aviation accidents are still occurring and on many occasions without the malfunctioning of the aircraft and systems. Not surprisingly, findings have pointed that due to the operational complexity, it is the failure of the human operator to anticipate and respond to threats or mismanaging the errors leading to an undesired state, which leads to a dire consequence. errors While it is impossible to foresee all plausible accident scenarios, it had been seen that inadequate situation awareness as well limited transferability of the training to line operations are almost always contributing factors and the next accident is just something completely unexpected.

Evidence-based Training (EBT) addresses this by attempting to use scenarios based on evidence collected in operations and training as a means to develop and assess the performance of human operators across the range of necessary defined competencies. EBT directs the instructor to analyze the root causes of accidents in context in order to correct inappropriate situational actions, rather than just repeating a practice with no real understanding as to how it could lead to an
accident. EBT also sees clearly successful safe and efficient operations as requiring an appropriate blend of both technical and non-technical areas. The key competencies identified therefore encompass what were previously termed both technical and non-technical knowledge, skills and attitudes, aligning the training content with the actual competencies necessary in contemporary aviation context. All these are articulated in the threat and error management (TEM) concept that forms the basis of EBT.

The TEM concept originated from a question of whether training contents are transferred to normal, everyday flight operations. This lead to a focus is on the most relevant threats and errors in that situation and their management, more specifically the response to the threats and errors, namely what were the threats and errors, agent of the error, response to the error (whether it was detected and by whom) and outcome of the error. As the TEM framework examines simultaneously the operating environment and the human operators working in that environment, performance is captured in its “natural” or normal operating context, and therefore the resulting performance is realistic, dynamic, and holistic. The TEM taxonomy lends itself well to quantifying the specifics of the environment and the effectiveness of performance in that environment, so the outcomes can be meaningfully diagnosed.

Threats are defined as events or errors that occur outside the influence of the human operator leading to increased operational complexity and requiring attention and management if safety risks are to be minimized. Sometimes they can be managed discreetly and sometimes they interact with one another further complicating the necessary management. In aviation, threats can be divided into environmental threats, which are outside the aircraft operator’s direct control, such as weather and aircraft operator threats, which originate within flight operations, such as aircraft malfunctions and ground problems. The TEM framework considers these complexities as threats because they all have the potential to negatively affect operations by reducing margins of safety.

Some threats can be anticipated, since they are expected or known to the flight
crew, like a congested airport that can be seen by watching other aircrafts during the approach. Some threats can occur unexpectedly, such as an in-flight aircraft malfunction that happens suddenly and without warning. Other threats may not be directly obvious to, or observable by, flight crews immersed in the operational context, although they may be uncovered by safety analyses. These include equipment design issues or shortened turnaround schedules. Regardless of whether threats are expected, unexpected, or not obvious, the human operator has to manage these threats and respond to them.

Threat management is a building block to error management and undesired aircraft state management. The threat-error linkage is not necessarily straightforward and it is not possible to establish a linear relationship, or one-to-one mapping between threats, errors and undesired states. However, archival data demonstrates that mismanaged threats are normally linked to flight crew errors, which in turn are oftentimes linked to undesired aircraft states. Threat management provides a highly proactive strategy to maintain safety margins in aviation operations by mitigating safety-compromising situations. Examples of threats are in the table below.

<table>
<thead>
<tr>
<th>Environmental threats</th>
<th>Organizational threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>➤ Weather: thunderstorms, turbulence, icing, wind shear, cross/tailwind, very low/high temperatures.</td>
<td></td>
</tr>
<tr>
<td>➤ ATC: traffic congestion, TCAS RA/TA, ATC command, ATC error, ATC language difficulty, ATC non-standard phraseology, ATC runway change, ATIS communication, units of measurement (QFE/meters).</td>
<td></td>
</tr>
<tr>
<td>➤ Airport: contaminated/short runway; contaminated taxiway, lack of/confusing/ faded signage/markings, birds, inoperative aids, complex surface navigation procedures, airport constructions.</td>
<td></td>
</tr>
<tr>
<td>➤ Terrain: High ground, slope, lack of references, “black hole”.</td>
<td></td>
</tr>
<tr>
<td>➤ Other: similar call-signs.</td>
<td>➤ Operational pressure: delays, late arrivals, equipment changes.</td>
</tr>
<tr>
<td>➤ Aircraft: aircraft malfunction, automation event/anomaly, MEL/CDL.</td>
<td></td>
</tr>
<tr>
<td>➤ Cabin: flight attendant error, cabin event distraction, interruption, cabin door security.</td>
<td></td>
</tr>
<tr>
<td>➤ Maintenance: maintenance event/error.</td>
<td></td>
</tr>
<tr>
<td>➤ Ground: ground handling event, de-icing, and ground crew error.</td>
<td></td>
</tr>
<tr>
<td>➤ Dispatch: dispatch paperwork event/error.</td>
<td></td>
</tr>
<tr>
<td>➤ Documentation: manual error, chart error.</td>
<td></td>
</tr>
<tr>
<td>➤ Other: crew scheduling event</td>
<td></td>
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</tbody>
</table>
Errors are “actions or inactions by the flight crew that lead to deviations from organizational or flight crew intentions or expectations”. Unmanaged and/or mismanaged errors frequently lead to undesired aircraft states. Errors in the operational context reduce the margins of safety and increase the probability of adverse events. They can be errors of commission or omission.

Error management is now recognized as an inevitable part of learning, adaptation, and skill maintenance. The TEM seeks to understand what types of errors are made under what circumstances (i.e., the presence or absence of which threats) and how operators respond in those situations. For example, do they detect and recover the error quickly, do they acknowledge the error but do nothing, perhaps because they believe it is inconsequential or will be trapped later, or do they only “see” the error when it escalates to a more serious undesired aircraft state? This is the heart of error management: detecting and correcting errors. However, approximately 45% of the observed errors in the LOSA Archive were errors that went undetected or were not responded to by the flight crew, which gives credence to an important point for effective error management: An error that is not detected cannot be managed. An error that is detected and effectively managed has no adverse impact on the flight. On the other hand, a mismanaged error reduces safety margins by linking to or inducing additional error or an undesired aircraft state.

Capturing how errors are managed is more than capturing the prevalence of different types of error. It is important to capture if and when errors are detected and by whom, the response(s) upon detecting errors, and the outcome of errors. Some errors are quickly detected and resolved, thus becoming operationally inconsequential, while others go undetected or are mismanaged. A mismanaged error is defined as an error that is linked to or induces an additional error or undesired aircraft state. The table below summarizes some of the errors that could arise.
When errors are not well managed, they sometime lead to a safety-compromising event called an undesired aircraft state (UAS). UAS is seen as a misapplication of flight controls, or incorrect systems configuration that results from operator error, actions, or inaction; and clearly reduces safety margins. Often considered at the cusp of becoming an incident or accident, undesired aircraft states must be managed by flight crews.

Examples of undesired aircraft states would include lining up for the incorrect runway during approach to landing, exceeding ATC speed restrictions during an approach, or landing long on a short landing distance limited runway. Events such as equipment malfunctions or ATC controller errors can also reduce margins of safety in flight operations, but these would be considered threats. As with errors, UASs can be managed effectively, returning the aircraft to optimally safe flight, or mismanaged, leading to an additional error, undesired aircraft state, or worse, an incident, or accident. Some of the UAS are listed in the table below.
Moving from Error to Undesired State Management

TEM gives a principled approach to examine the dynamic and challenging complexities of the operational context in human performance and highlighting that threats and errors must be managed as they can generate undesired aircraft states that will directly affect safety.
It can be seen that the undesired state management is as important as threat and error management given its potential for unsafe outcomes and in itself an opportunity to prevent an accident occurrence. It is only when error is mismanaged that the undesirable state happens. This is when the undesirable state management should be activated. It is therefore critical for the human operator to know when to switch from error management to undesired state management. An example to illustrate this is when a flight crew selects a wrong approach in the Flight Management Computer (FMC). The flight crew subsequently identifies the error during a crosscheck prior to the Final Approach Fix (FAF). However, instead of reverting to a basic mode (e.g. heading) or manually flying the desired track, both flight crew attempts to reprogram the correct approach prior to reaching the FAF. This caused the aircraft to fly through the localizer, descend late, and the approach becomes unstable. The flight crew is “locked in” to error management instead of switching to undesired state management. Hence, in the training of flight crews, it should be emphasized that when the aircraft is in an undesired state, the basic task of the flight crew is undesired aircraft state management instead of error management. This example also illustrates how easy it is for operators to be locked in to the error management phase.

In addition, it is important to see that there is a clear differentiation between undesired states and outcomes. Undesired states are transitional states between a normal operational state (i.e., a stabilized approach) and an outcome. Outcomes, on the other hand, are end states, most notably, reportable occurrences (i.e., incidents and accidents). An example would be as follows: a stabilized approach (normal operational state) turns into an unstable approach (undesired state) that results in a runway excursion (outcome).

The training and remedial implications of this differentiation are significant. While at the undesired state stage, there is still a possibility of recovering the situation, returning to a normal operational state. Once the undesired state becomes an outcome, recovery of the situation, return to a normal operational state, and restoration of margins of safety is not possible. To recognize the onset of the undesired state, the concepts of anticipation, recognition, and recovery become important. The key to anticipation is accepting that while something is likely to go wrong, one can’t know exactly what it will be or when it will happen. This reinforces
vigilance that is the key to recognizing adverse events and error. While it is desirable that recognition will lead to recovery, it is when an error escalates to an undesired state that recovering adequate safety margins must become the first line of action. For example, the operator mistakenly enters data for 26R instead of runway 26L. This error is not detected by the flight crew on a SOP required cross-verification. Once the incorrect entry is executed and the airplane starts flying on a profile to the wrong runway, the flight is considered to be in an undesired state. At this point, the action to take could be to analyze what is wrong with the automation to fix the problem or simply disconnecting the autopilot and manually execute the approach to the correct runway. The latter would be more effective as it focuses effort on recovering from the undesired state.

**Training for Anticipation, Recognition and Recovery for the Undesired States**

Any training for the undesired state management must address making anticipation, recognition, and recovery elements to second nature to the human operator and overcome the lock-in to error management that tends to prescribe a set of analytical procedures leading to corrective actions for the error rather than the current undesired state that the error has evolved into. Existing error management training involves knowing and becoming able to carry out the “correct” operational modes and takes the form of instructor-led classroom training, computer-based training and an element of on-the-job experience if the situation or incident can be simulated safely. It will not only time-consuming but the efficacy of such training mode for undesired state management may not meet the desired outcome as it is hard to create realistically the experience of the environment. A cognitive transition of the theoretical knowledge gained into practical experience will then have to occur before any application can be carried out. The situation is aggravated by the fact that there is a plethora of undesired states (see table below) ranging from immediate, complex, control degradation and extensive management of consequences independent of the operations or environment.
So far, it has been argued that the operational context affects human performance. More specifically, there is an ongoing interaction between the person and the environment beginning with a dynamic orientation to the situation, the opportunity to reflect the past experience, present perception and future consequences of handling the situation. This dynamic reflection contains logical-conceptual, imaginative, conscious and unconscious components, which enables the development of mental models of events. For example, the air traffic controller may first notice a change in trajectory, and then comprehend that this means aircraft are now on a converging trajectory, and depending on whether recovery is done or an accident arising from error management lock-in, the person will finally understand when, in the future, a conflict may take place and how serious it will be. Using the diagram below, it can be seen that any situation encountered over time will generate cues (like proxy indicators that could be part of the anticipation cognitive repertoire) which then triggers the matching of the present situation with internalized known patterns. Once there is a match, the pattern is recognized and its associated action script will be activated to affect the situation at hand. The action script is created over time and driven by the person’s mental models acquired over time. Hence, training should therefore focus on creating cues, scripts and mental models. Training should provide as many features of different situations to build prior experience and then exercises to execute rehearsals of as many courses of

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description of required crew performance</th>
<th>Examples</th>
</tr>
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<tbody>
<tr>
<td>immediacy</td>
<td>System malfunctions requiring immediate and urgent crew intervention or decision</td>
<td>Fire, smoke, loss of pressurization at high altitude, failures during take-off, brake failure during landing</td>
</tr>
<tr>
<td>complexity</td>
<td>System malfunctions requiring complex procedures</td>
<td>Multiple hydraulic system failures, smoke and fumes procedures</td>
</tr>
<tr>
<td>degradation of aircraft control</td>
<td>System malfunctions resulting in significant degradation of flight controls in combination with abnormal handling characteristics</td>
<td>Jammed flight controls, certain degradation of FBW control</td>
</tr>
<tr>
<td>loss of instrumentation</td>
<td>System failures that require monitoring and management of the flight path using degraded or alternative displays</td>
<td>Unreliable primary flight path information, unreliable airspeed</td>
</tr>
<tr>
<td>management of consequences</td>
<td>System failures that require extensive management of their consequences (independent of operation or environment)</td>
<td>Fuel leak</td>
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</table>
action as possible. Over the course of the training, the main objective would be to let the operator see how the action will affect the situation as intended, and in the process, revise their theory of the situation and adapt their actions accordingly.

Another consideration is that in undesired state management, there are substantial difficulties when faced with a threat or error that is a surprise or an unforeseen event. The element of surprise is best covered by a concept called “sense making” that argues people tend to engage with the elements in their environment as well as their inability to rebuild some sense of order when a situation that disrupts these elements (often retrospectively refer to as an unsafe situation). Its basic idea is that reality is an ongoing accomplishment that emerges from efforts to create order and make retrospective sense of what occurs (Klein, 1993). People try to make contextual rationally accountable to themselves and others. It is constructed from vague questions, muddy answers, and negotiated agreements that attempt to reduce confusion. Instead of asking “where should we go, when do we take a stand, or what should our strategy be?”, they face the more basic, the more frightening feeling that their old labels were no longer working. They are outstripping their past experience.
and not sure either what was up or who they were. Interestingly, this disorganization state is not all that rare in everyday life, for example when people are thrust into unfamiliar roles, some key roles left unfilled, the task made more ambiguous, role system discredited and all of these changes happen in a context, they can combine into something out of control.

In a paper on collective sense making, Weick (1992) examined a group of firefighters who perished while firefighting. He found that most of them perished because they would not “drop their tools and run”. As firefighters, they were too well trained into the belief that their tools were essential for survival and through rote-training that belief became internalized. Even though it was obvious that their attempts to fight the fire were futile, and despite being surrounded by the raging fire, they just did not do what would have been intuitive to others – drop their tools so as to lighten their loads and run for their lives away from the fire. In the same way, when people encounter surprises, they hang on to the familiar organization of the social structure around them, try to fit the changed situation into their existing frame of reference and even attempt to “repair” the situation with the tools that they have been trained to have and use in all situations. Sensemaking therefore points to the importance of inculcating a training philosophy that embraces situational awareness of when to drop one’s tools and run. In this paper, it points to the need for training to be adaptable and be prepared for contingent actions that may be outside the realm of the organized structure of their work.

**The Case for Using Virtual Reality for Undesired State Training**

In a research on using virtual reality technology for aircraft visual inspection training, degree of immersion and presence felt by subjects in a virtual reality simulator were compared to a PC-based aircraft inspection simulator. The results showed that the Virtual Reality (VR) system was better and preferred over the PC-based training tool (Vora, e. al. 1988). In a separate experiment in assessing the effectiveness and efficiency of IVR training for radiation awareness in a nuclear power plant, IVR trained group received significantly less radiation exposure and
completed the activities on an average of one minute faster\textsuperscript{1}. A study by Sacks, Perlman, & Barak (2013) showed that construction workers’ ability to identify and assess risks is the key factors that determine their behavior and thus their safety. While these can be acquired through training and experience, the effectiveness of conventional safety training has been questioned. Their research compared traditional classroom training with visual aids and using a 3D immersive VR power-wall. Significant advantage was found for VR training, as VR training was more effective in terms of maintaining trainees’ attention and concentration. Training with VR was more effective over time, especially in the context of cast-in-situ concrete works.

The paper has so far attempted to make a case for EBT and the need for actual situational context and dynamic content that allows the person to interact differently with different consequences. This points to the need for a new methodology and given the need for improved training and the advantages of training using VR, incorporation of VR in EBT is strongly recommended. – Virtual Reality (VR). VR can shorten training time and increase training effectiveness by offering “highly realistic” training that will make training outcomes seamless with practice so as to enable operators to anticipate plausible and realized situations that are undesired states, recognize when they happen so as to shift into undesired state management mode and also be equipped with “dropping one’s tools” to quickly create new order in these “crises” situations so as to minimize the occurrences of dire consequences.

**A VR EBT Example**

Any VR training would involve the choice of a VR display and the construction of 3D models with interactivity based on the context and content of the training outcome in mind. The common VR display devices used are the Head-Mounted Displays (like the HTC Vive, Occulus Rift VR or Google Daydream), the Augmented Reality Displays (like the Android or IoS tablets, Smartphones, or Microsoft HoloLens) as well as the CAVE System. The CAVE is an Immersive 3D VR system theatre with projection
display screens that surround a viewer and allows perception of the virtual environment as almost real in scale. Users are able to move to some extent within the space itself and to travel longer distances by hotspot teleportation or using an attached omni-directional treadmill. Another important characteristic is the quality of the virtual featuring realistic objects, lighting and shadows, surface structures, colors, and views out of windows, and offering real-time interactivity.
For the VR content, creation can be done based on any storyboarding and incorporating any feature. For example, the element of surprise is important in undesired state training. This element of surprise is difficult to achieve in non VR training. In VR, it is possible to give consideration towards variations in the types of scenario, times of occurrences and types of occurrence, so that operators do not become overly familiar with repetitions of the same scenarios. Variation is the focus of the EBT but it is not left to the discretion of individual instructors in order to preserve training integrity and fairness. Another advantage is optimization. Context and content can be customized using specific environment and operations as well as even for the individual based on data analysis of their previous EBT sessions so as to enhance the EBT, resulting in improved effectiveness and efficiency.

In this illustrative project, a 3D model of a generic civilian aircraft sitting at the airside is created.
The threats that can lead to ramp agent error are then identified and each of these can then brought into the above 3D model as part of the interactivities. A lesson plan is built around each of these threats, mismanagement leading into error and then mismanagement of the error to move the situation into an undesired state and finally either an inconsequential outcome or an accident. There are several endings for each threat, depending on what action was taken. All these scenarios, consequences and outcomes are constructed from the evidences of real aviation-related incidences and using a similar chart as shown in Annex A.

Conclusion

VR-EBT brings about a quantum improvement in learning and behavioral outcomes. Its high realism environment and interactive content allow real-life scenarios played out in real-time and provide exposure to various simulations of situations. Users can learn feel, and response to the various stimulations; and through the stimulation of immediate feedback of their cognitive responses or reaction will trigger a better learning effect, retentivity and outcome and in the process help them to directly apply the experience to actual situations. The VR-EBT embraces the call for EBT in Aviation Training as well as makes explicit the TEM concepts for minimizing safety
risks and occurrence of accidents. It will certainly enable a quantum leap in training productivity to be achieved, reduce training resources required, shorten the training time needed to achieve competency, as well as improve the overall quality, delivery, and realism of the training.

REFERENCES
(to be provided upon request)

ANNEX A