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Exploring the integration of live, virtual, and constructive environments in fighter pilot training through Link-16: lessons learned regarding training aspects

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Abstract
Live, Virtual, and Constructive (LVC) training has gained attention as a cost-effective and scalable approach to improve fighter pilot training. Despite its potential, achieving a highly interoperable LVC environment remains a challenge, limiting its widespread implementation in the near future. However, integrating existing technologies and operational datalinks offers opportunities to enhance training effectiveness, even with some limitations in interoperability and interaction. This study investigates the feasibility and benefits of incorporating LVC elements into training scenarios. In October 2023, a synthetic environment combining a virtual fighter and constructive elements was integrated into the large-scale Frisian Flag exercise. Through Link-16 datalink and ultra-high-frequency (UHF) radio connectivity, virtual and live elements exchanged data, allowing the virtual simulator to participate in Offensive and Defensive Counter Air missions alongside live pilots. Post-training evaluations indicated that the virtual and constructive elements positively impacted the training value for live pilots, while pilots operating the virtual simulator also reported benefits, albeit to a lesser extent than in live sorties. This paper focuses on the training outcomes within the context of Frisian Flag and seeks to provide broader insights for diverse training scenarios.

Keywords
Live, virtual, and constructive training, fighter pilot training, training effectiveness, synthetic training environments, military aviation

1. Introduction

In an LVC training live (L), virtual (V), and constructive (C) elements are combined in a single training environment where these elements can interoperate with each other. LVC training has been argued to reduce training cost, enrich training scenarios, and to be flexible and scalable. Research into the technology required for LVC, as well as its training applications, is ongoing. Investigations into technology focus on aspects such as LVC architecture, datalinks (e.g. P5 pods),[1] radio waveforms[2] and computer-generated forces.[3] Training applications are examined in terms of training value,[4,5] allocation of live, virtual, or constructive states,[6] and fidelity requirements.[7] However, there is limited research that comprehensively investigates both LVC technology and training applications. In addition, there is a lack of hands-on experience in training applications.[4] Much of the research is conducted in artificial settings through workshop sessions or simulation exercises that simulate live assets under peacetime

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conditions (e.g. performing unclassified maneuvers). While such research yields valuable insights, there is a need for more hands-on experience during live training and exercises that integrate technology and training research. There are several practical applications of LVC training in fighter jet training. Only few lessons learned are reported due to the often commercial and/or confidential nature of these applications, resulting in limited publication of results. Notable examples include the French Air and Space Force's use of the JEANNETTE system during daily training and exercises,[8] the United States Air Force's utilization of Secure Live Virtual Constructive Advanced Training Environment (SLATE) pods during the Valiant Shield exercise in Guam,[2,9] and the incorporation of LVC in the Tactical Leadership Program in Spain.[10]

The Air LVC research program[11] aims to create a demonstrator showcasing LVC technology to explore its potential in enhancing training, such as investigating the improvements it can bring. The ultimate goal of LVC is to establish a fully operational and integrated LVC environment, enabling operators to experience realistic high-end training with realistic blue and red force. This environment should be scalable and modular, capable of operating at any scale required, from routine day-to-day training to large-scale international exercises. It should also be compatible with various platforms and entail minimal setup requirements. However, while ongoing research aims to realize this vision, such a comprehensive environment is not anticipated in the near future for the Royal Netherlands Air Force (RNLAF). Therefore, it is imperative to explore intermediate solutions to enhance the training opportunities of military pilots promptly by using existing technologies.

This study examines a potential intermediate solution by employing the Link-16 datalink network for LVC applications, as part of the Air LVC research program. Within this program, a conceptual architecture was devised to outline how LVC could be implemented using the Link-16 datalink. To illustrate this intermediate solution, the conceptual architecture is translated into a solution architecture and network configuration. The technical solution and insights gained are detailed by Petermeijer et al.[12] and Lemmers et al.[13] An intermediate solution can provide an effective cost-benefit balance, as it can often be created using existing assets, such as simulators and technical datalink technology, thereby minimizing additional costs and maximizing resource utilization. In this study, we focus on findings related to training, conducted within the context of LVC use during the large-scale exercise Frisian Flag, providing insights into this specific application of LVC. Nevertheless, the present research aims to derive more general insights applicable across various training scenarios (e.g. day-to-day training, large-scale exercises, and diverse mission types) as well as potential applications in the future. The following research questions are specified:

1. How is the training value related to the LVC setup perceived by the airborne pilots?
2. How is the training value of the exercise perceived by the pilot of the virtual entity?
3. How can an LVC environment be applied in pilot training to increase training value?

1.1. Related work

The utilization of simulators has emerged as a standard practice for training across diverse fields such as aviation, medicine, and maritime operations, offering an efficient and safe means of skill development.[4,7] The use of simulators has evolved to distributed simulation where multiple simulators are operating in one network and scenario supported by computer-generated forces.[3,7] A next step to further improve training is Live, Virtual, Constructive (LVC) training, which integrates real pilots in real aircraft, real pilots in simulators, and computer-generated forces (such as simulated pilots in simulated aircraft or ground assets) in collaborative training scenarios.[5,7] LVC can facilitate flexible and effective training, enabling pilots in real aircraft to train alongside pilots in simulators and computer-generated forces, thereby enhancing training realism, efficiency and effectiveness.[5–7] LVC can increase availability for complex training scenarios. The need for complex training environments rises with modern, fifth-generation platforms, but current demand for these scenarios exceeds availability.

However, the full implementation of LVC in large-scale exercises encounters obstacles such as technological limitations, availability constraints, compatibility issues, and security concerns. Despite these challenges, ongoing research efforts focus on harnessing the potential training benefits of LVC, including improved scalability, immersion, realism, and evaluation of tactics.[4] Nevertheless, there are still unanswered questions regarding integrating LVC effectively in training and enable a safe integration of LVC, for example, preventing negative training due to current limitations or potential confusion between LVC elements.[4,7]

Addressing these challenges necessitates aligning LVC scenario design with training objectives to ensure effective training outcomes for both live and virtual pilots. Researchers emphasize the importance of developing effective exercise management tools and methods to optimize training value and mitigate negative training and safety risks in LVC training scenarios.[4–6]

In essence, while LVC training holds promise for revolutionizing training methodologies and enhancing training outcomes, further research is imperative to fully comprehend its capabilities and address existing challenges. Through collaborative efforts and ongoing innovation, LVC training has the potential to redefine training practices and elevate the proficiency of professionals.[4–6]

1.2. Frisian Flag exercise

Frisian Flag is an international military exercise hosted in the Netherlands at Leeuwarden Air Base, engaging various NATO allies and partner nations, including the Netherlands, United States, Germany, and the United Kingdom, among others. Its core aim is to practice multinational mixed fighter operations against a wide variety of airborne and ground-based threats. Scenarios included but were not limited to air defense missions, escort missions, and striking fixed and moving targets on land and at sea. As well as integration with land and maritime forces. With the tensions in Eastern Europe and the war in Ukraine, this is essential training for the participants.[14]

2. Method

This section describes how the research is conducted, what instruments were used and who were participating. All data were collected during Frisian Flag '23. The section concludes with a brief description of the general architecture of the LVC environment.

2.1. Instruments and participants

Both interviews and questionnaires were employed to collect the results needed to answer the research questions. The content of the instruments was refined through iterative discussions with former fighter pilots to ensure the questions were meaningful. Every instrument is discussed separately. The data gathered by the instruments will be analyzed qualitatively.

2.1.1. Questionnaire. The questionnaire was carried out during the mass debrief of a mission for each day of the exercise. A mass debrief is an evaluation session where all participating pilots come together to systematically review the mission. The goal of the questionnaire was to collect the opinion of the airborne pilots on their training experience in relation to the virtual entity. The answers contribute to all three research questions. The topics covered in the questionnaire are integration of the virtual entity, collaboration with the virtual entity and perceived added training value as a result of the virtual entity. The questionnaire consisted of 11 questions and took about 2 minutes to fill out, and was filled out voluntary (see Appendix A for the entire questionnaire). It was kept brief to avoid requesting an excessive investment of the pilots' time after their flights, which time is often used to rest, debrief, and prepare for the next flight.

The questionnaire resulted in 84 usable responses during the 2-week exercise. Two responses were deleted due incomplete answers. Therefore, the total response was 86. Sixty responses originated from pilots that flew blue air and 24 flew red air. It is possible that the same pilot completed the questionnaire multiple times throughout the course of the exercise. The exact number of responses from one pilot is not monitored. During the research, it was noted that pilots flying in the same twoship or fourship formation completed the questionnaire together. As a result, certain responses reflect a collective team effort rather than individual input. In the analysis, these pairwise responses were treated as individual input, as it was impossible for the researchers to identify and separate these reliably.

2.1.2. Interviews with simulator pilots. Pilots operating the simulator during the exercise were interviewed in a semi-structured format. The interviews aimed to gain insight in all three research questions. The interviews covered largely the same subjects as those addressed in the questionnaire. In addition, the technical implementation of the simulator was a subject of the interview. Pilots were asked about their opinion of the degree of realism of various technical systems, such as radar and Link-16. Next, pilots were asked how the simulator and LVC capabilities (and deficiencies) influence the training value. At last, the pilots were asked about the efficient use and deployment of LVC within Frisian Flag specifically and potential use in other training events (e.g. day-to-day training). Four RNLAF F-35 pilots participated in the interview after operating the simulator. While the pilots had varying levels of experience, all were seasoned and experienced operators.

2.1.3. Interviews with live pilots. Semi-structured interviews were conducted with pilots that were participating in the exercise as live elements and had a leadership role (e.g. flight lead or mission commander). The goal of the interview was to gain in-depth insights in the same subjects as the previously mentioned interview. Integration of the virtual entity (simulator) was also a subject, but more from the perspective of the airborne pilot. Three RNLAF F-35 pilots and one Belgian Air Component (BAC) F-16 pilot were interviewed after participating in the exercise as live entity. One RNLAF F-35 pilot was also featured in the interview with simulator pilots. While the pilots had varying levels of experience, all were seasoned and experienced operators. The pilots fulfilled different roles during the exercise, including roles in Blue Air, Red Air, exercise management, and various leadership positions.

2.2. Training scenario

During Frisian Flag participating pilots were trained to perform complex missions in international cooperation at a higher intensity. Defensive Counter Air (DCA) and Offensive Counter Air (OCA) missions were conducted twice daily. The primary aim of a DCA mission is to protect a designated area, location or asset from hostile airstrikes, predominantly involving air-to-air (A/A) combat engagements. An OCA mission aims to establish air superiority over an adversary-controlled zone, facilitating ground target attacks. This involves both A/A combat and strategic targeting of enemy air defense or ground assets, known as air-to-ground (A/G) combat. Mission categorization distinguishes between A/A or A/G combat for friendly (blue air) or opposing (red air) forces. Fighter pilots operated as either flight leads or wingmen. A flight lead commands a group of four, sometimes two, aircraft, including their own. Besides that, the mission commander oversees the tactical planning, execution and debriefing process.

Twice daily, approximately 20 to 30 aircraft participated in a training scenario above the North Sea and northern Netherlands, divided into blue and red forces. The participating fighter jets include Eurofighter Typhoons, F-16s, F/A-18s, F-35As, and F-35Bs. In addition, the AH-64 Apache, NH90 maritime helicopter, C-130 Hercules, and Multinational MRTT Unit take part. The LVC setup was only active during the first morning wave of each day, introducing a twoship consisting of one virtual and one constructive entity. The twoship was tasked to be nonessential to the training scenario, allowing for potential technical failures to be accounted for, but its tasking enabled collaboration and interaction with other formations, providing a sufficient test for the LVC setup.

2.3. LVC architecture

This section specifies the general architecture used to create the LVC training environment. The demonstrator used a Link-16 connection between a live and virtual aircraft and was part of Frisian Flag at Leeuwarden Air Base in October 2023. The F-35 Emulated Non-Operational Flight Program Interoperability Xperience (FENIX) (formerly known as ‘‘Evidence-Based Simulator’’ or (EBS), built by NAVAIR, was used in the demonstrator. The FENIX is a portable, medium-fidelity simulator that utilizes a cockpit mock-up and four large out-the-window screens to immerse the pilot (see Figure 1). It features a representative flight model and simulates various sensors of an F-35, with varying fidelity levels per sensor. In addition, the simulator includes radio communication, jamming and countermeasures, as well as weapon systems.

Alongside the FENIX, a constructive F-35 was added to form a twoship. Next-generation threat system (NGTS) was used to add constructive entities to the scenario. NGTS is a program from NAVAIR, designed to enhance military training. It provides high-fidelity simulations of red and blue computer-generated forces (CGFs), enabling realistic and complex training scenarios. NGTS can simulate CGFs across several domains, including aircraft, ground units, surface and subsurface entities and their weapons, allowing for complex joint missions. No CGFs other than the constructive F-35 was added.

The week prior to Frisian Flag ’23 was used to setup an operational LVC environment. However, throughout the whole exercise the LVC environment was refined and upgraded. The initial plan was for the FENIX to participate as a generic fighter simulator, serving as a protected entity that would require safeguarding and escort by other assets in the scenario. However, integration and development went faster and more smoothly than anticipated, despite immaturities of the simulator, the exercise director chose to have the FENIX participate as an F-35 instead of a generic fighter. Foremost, the goal of this demonstrator was never to fully replicate an F-35. The architecture is displayed in Figure 1 and consists of the elements mentioned below. Further details on the architecture and Link-16 messages used in the exercise are provided in Petermeijer et al.[12]

(1) *Live players*—Red and blue aircraft and C2-cells connected via UHF/VHF radio and a Link-16 network with a separate blue and red subnet so each side had a separate surveillance picture at their disposal.
(2) *Virtual F*-35—An F-35 simulator (i.e. FENIX) interoperable with other elements via the DIS network, including DIS voice messages for live voice communication.
(3) *Constructives*—A constructive threat environment was used to generate both blue and red elements, including the constructive wingman.
(4) *Link*-16 *bridge*—Software application which translated simulated tactical data messages (e.g. SISO-J or JREAP) to a message form which is understood by Link-16. It also extracted information to represent the live elements in the synthetic world.
(5) *Radio bridge*—An application which translated the digital voice communication to an analogue signal that can be transmitted via UHF/VHF.

2.4. Analysis

The raw data from the questionnaire underwent analysis to derive descriptive statistics. Notably, no statistical tests were conducted as they were deemed irrelevant for this

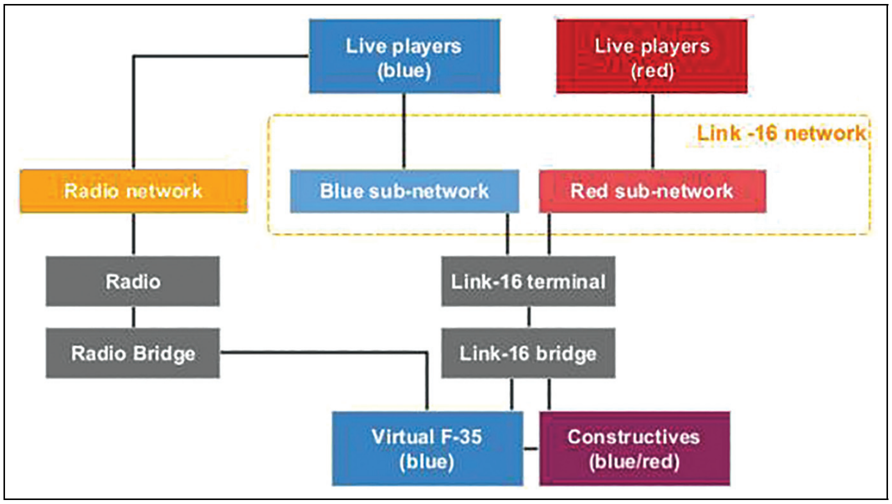

Figure 1. The general architecture of the LVC environment used in Frisian Flag '23.

study. The primary focus is to present qualitive key insights rather than statistical details.

For the interviews, participant responses were documented individually in a meeting report. Following the interviews, researchers thoroughly reviewed and merged the results, identifying common themes, experiences, and any apparent contradictions. The processed outcomes, representing a synthesized understanding of the findings, are then detailed in the Results section.

All outcomes were reviewed and discussed with former fighter pilots to ensure that the results are interpreted correctly and meaningfully.

3. Results

3.1. Questionnaire

The results of the questionnaire are presented in three sections corresponding with the different subjects. When reading the results, it is important to keep in mind that the goal of the demonstrator was never to fully replicate a realistic F-35.

3.1.1. Response rate. The response rate on the questionnaire was expected to fluctuate during the course of Frisian Flag '23. The response rate in Table 1 showed that the response rate for blue as well as red air dropped over time. It is noteworthy that the response rate decline in the first week is stronger for red air than for blue air. This difference between blue and red responses is probably attributed to the limitation of the virtual twoship being solely connected to the Link-16 network of blue air during that period. Red air was not able to interact with the virtual twoship (via Link-16) in the first week.

On the tenth of October, 7 days of flight into the exercise, the virtual twoship was for the first time stably visual on the Link-16 network of red air. Since the virtual entity was now presented in the red air cockpits, it could be successfully targeted and engaged, resulting in the kill call of the virtual element. In the following days, a small increase of response from red air was observed probably because their environment in regard to LVC changed significantly.

3.1.2. Situational awareness and safety. Participants were surveyed regarding their observations on differences between live and virtual elements, aside from visual limitations. Out of 84 responses, 27 participants (32%) reported experiencing disparities. Specifically, instability in Link-16 tracks was mentioned 19 times, and the absence of the F-35 specific MADL-datalink was noted twice. However, reports of unstable Link-16 tracks decreased over time, likely due to enhancements in the LVC environment and the overall Link-16 network.

Regarding situational awareness, participants were asked if they perceived equality between live and virtual elements. Results mirrored those of the previous question, with situational awareness often lacking initially but becoming similar when connections stabilized because of the increases in quality of the Link-16 network stability.

Concerning safety and training rules involving virtual elements, four participants expressed concerns. One mentioned that unstable situational awareness in virtual elements could confuse players at similar altitudes. In addition, two participants noted issues with clearance to descend through the altitude box of a virtual twoship when it was in close proximity, prompting them to delay descent until the twoship moved away. It was agreed that all

Table 1. Response rate of the questionnaire per day.

Date	Blue air	Red air	Total
02-10-2023	12	6	18
03-10-2023	11	6	17
04-10-2023	11	1	12
05-10-2023	6	1	7
06-10-2023	6	2	8
10-10-2023	7	2	9
11-10-2023	2	3	5
12-10-2023	5	3	8

participants in the exercise, both virtual and live, would be treated as live elements, and the pilots acted accordingly. The call to descent was likely due to Fighter Control's unawareness of the virtual elements' presence.

3.1.3. Mission execution. Participants were surveyed about task and mission execution within the LVC environment through six questions, answering either "yes" or "no" with the option to provide explanations. The results, depicted in Table 2, highlight the effectiveness of communication facilitated by the virtual entity's connection to UHF and VHF radios. However, shared situational awareness was rated lower.

Few deconfliction issues were reported, but a notable minority (9 responses) expressed dissatisfaction with the tactical execution of the gameplan with the virtual entity. One respondent, an F-35 pilot, attributed this to the virtual entity's limited sensor capabilities, specifically citing the absence of the MADL-datalink and simulated sensor functionalities.

Participants did not perceive additional cockpit workload when collaborating with the virtual entity. Furthermore, no significant problems were reported regarding the virtual entity's provision of data or information necessary for debriefing.

3.1.4. Overall impact. Regarding the overall impact of the virtual entity in its current form and setup, participants unanimously agreed that it added value to the exercise. Suggestions for improving the LVC environment included enhancing the stability of the Link-16 connection, expanding the types of Link-16 messages that virtual elements can transmit (e.g. including aircraft type in a Link-16 track), and enhancing the simulator's F-35 capabilities, particularly in terms of sensors and MADL-datalink functionalities.

3.2. Interviews

Fighter pilots who operated the simulator during the exercise were interviewed as well as pilots that participated in the exercise as live entity and had a leadership role (e.g. flight lead or mission commander). The results are structured according the following five themes:

1. Collective training value: the added training value of the virtual entity on a collective level. Emphasizes team-based operations, requiring pilots to coordinate, communicate, and execute tactics effectively within a group or multi-unit mission environment.
2. Individual training value: the added training value of the virtual entity on an individual level. Focuses on developing a pilot's personal skills, proficiency, and core competencies required for independent operation of the aircraft.
3. Integration in the exercise: how is the virtual entity integrated in the exercise, how is this perceived and how it can be improved.
4. Day-to-day training: the added value of the current or similar LVC setup to day-to-day training.
5. Alternative training systems: comparison with alternative training systems, such as Embedded Training Systems or Live Red Air.

3.2.1. Collective training value. Pilots noted that the inclusion of each extra asset contributes to the complexity of both planning and execution of the gameplan. The introduced assets, comprising one virtual and one constructive aircraft,

Table 2. An overview of the responses on the questions regarding mission execution.

Interview item	Yes	No	No answer/not relevant
Was communication effective with the virtual entity?	39 (46.43%)	8 (9.52%)	37 (44.05%)
Did you have effective shared situational awareness?	34 (40.48%)	23 (27.38%)	27 (32.14%)
Did you have perceived deconfliction problems?	3 (3.57%)	72 (85.71%)	9 (10.71%)
Was the tactical execution of the gameplan effective with the virtual entity?	41 (48.81%)	9 (10.71%)	34 (40.48%)
Did you experience cockpit workload differences in collaboration with the virtual entity?	1 (1.19%)	52 (61.90%)	31 (36.90%)
Did you have sufficient data for debrief in regard to the virtual entity?	33 (39.29%)	6 (7.14%)	45 (53.57%)

were regarded as realistic additions to the exercise. The airborne pilots benefited from this addition as it allowed for the realistic execution of a task that would have been left out when these elements were not present. The absence of these assets might have resulted in a less complex scenario, thereby reducing the training value.

This state of the FENIX simulator does not fully replicate an F-35, making it challenging to realistically execute certain tasks typical for an F-35. Consequently, there is uncertainty regarding the most efficient integration of the current simulator into the exercise. However, it was clear that the addition of one or multiple virtual assets is beneficial to the collective training value.

3.2.2. Individual training value. The pilots in the simulator stated that the planning process closely resembles that of a live operator. The planning process is a significant portion of the training value of a large-scale exercise, especially for inexperienced flight leads or wingmen preparing for their flight lead upgrade. An inexperienced wingman may already benefit from operating the virtual wingman position. Some extra actions were needed by the sim operator during the preparation phase, such as briefing the engineers on among others weather, waypoints, and coordinates of ground assets. Incorporating virtual elements expands the participation and training opportunities for more individuals.

Pilots indicated that the gameplan execution is realistic in the simulator. The decision-making process is equal in comparison to that of a live pilot. It is expected that the acquired experience from the simulator contributes to improved gameplan execution when performing live exercises/missions. This is due to more exposure and practice whenever a setup like this is available and additional sorties can be flown on the simulator.

One of the contributing factors to the individual training value is the Pilot Vehicle Interface (PVI). The fidelity of PVI is sufficient, which also adds to the level of immersion. The information from the Link-16 datalink was correctly and realistically visualized which enabled the operator to fully integrate in the gameplan alongside live elements.

It became apparent that the simulator operator was not only aiding the live elements but also gaining valuable training experience himself. However, five elements were observed that reduced the individual training value of the operator. As mentioned before, it was never the goal to fully replicate a realistic F-35 in this experiment.

1. The simulated F-35 was not connected to the MADL-network, whereby the simulator operated on different data as live F-35 aircraft. This hinders to fully integrate with live F-35 aircraft, but is less apparent when the virtual F-35 aircraft fly a separate formation. In addition, FENIX simulators have the capability to simulate MADL communication between each other.
2. The absence of MADL led to an abnormal process of targeting and therefore the tactical execution shows a slight deviation relative to live execution.
3. A Threat Warning System was missing for the simulator pilot. The current LVC environment did not exchange electromagnetic (EM) data. Hence the actions in the EM spectrum from a player in one environment were not realistically detectable by players in the other environment. Therefore, the Treat Warning System in the FENIX could not be triggered for example.
4. The simulator in its current state does not have full sensor capabilities, which limits the pilot in carrying out its task realistically.
5. No matter how sophisticated and immersive the simulator is, it will never equal the experience of live flying and thus the perceived mental load will not be the same. The operator does not experience the full flight experience (e.g. G-forces or the urgency of safety risks) in a simulator, which could bring down the perceived mental load. The execution of the gameplan is experienced as easier in the simulator because of the decreased mental load.

3.2.3. Integration in the exercise. Pilots described that trust in the technology is key for the willingness of operators to use it. It requires time to demonstrate the added value and gain trust. If the ongoing integration of the virtual entity encounters failures, trust and willingness may erode, even if it is a one-time issue. Therefore, it is important to take this process into account during integration. During Frisian Flag, pilots observed the added value and therefore the LVC setup gained trust after each day. This led to increased responsibilities and more complex tasks for the virtual elements, ultimately resulting in their full participation in the gameplan.

One pilot emphasized that deploying virtual and constructive elements relies on airspace and asset availability, with live elements preferred due to their perceived higher training value. However, if complexity is necessary and there is a lack of live assets—which frequently occurs—virtual and constructive assets can be integrated to operate within a single altitude box, thereby mitigating concerns about airspace congestion.

In terms of safety, the approach was taken to treat virtual and constructive elements like any other aircraft in both planning and execution. When fewer restrictions are applied, dangerous situations could occur when there is confusion, such as mistaking a live entity for a virtual one. Distinct symbology on Link-16 was mentioned as potential measure to better differentiate between entity states. Besides that, one pilot opted that safety risks can be apparent when a live pilot merges with virtual and constructive aircraft. The term ''merge'' is used to specify the transition from beyond visual range to within visual range. The amount of aircraft observed in real world at merge can deviate from the amount of aircraft visualized on Link-16 whenever virtual or constructive elements are present. Three potential mitigations were mentioned to incorporate:

1. In A/A-combat, prioritize virtual or constructive entity elimination first in a formation to maintain alignment with real-world elements, even if the live entity was targeted.
2. Ground-Controlled Interception (GCI) can mitigate confusion by announcing the combination of the adversary formation.
3. Use distinct symbology to distinguish between entity states, enhancing clarity during operations.

A prerequisite to train a meaningful ''merge'' is to have at least one live aircraft in the adversary formation.

One pilot observed that an agreement for targeting under a situation of instable Link-16 connection could benefit the integration of LVC. The network instability can lead to the inability to establish a target lock. A possibility is to agree to call a shot when the situation was optimal for firing, but network instability prevented locking onto the virtual entity. This could enhance realism and integration in the meantime, but ultimately a stable connection is required.

SAM-1 tends to prioritize targeting live elements over virtual ones. SAM-1 (Surface-to-Air Missile) is a red operator that coordinates and calls engagements and shots for the SAM-sites in the scenario. Calls are made based on the proximity of a blue aircraft and the range of a specific SAM-system. During Frisian Flag, SAM-1 opted not to target a nearby virtual entity, highlighting the lack of established protocols for such situations. Agreements could be made to optimize SAM deployment strategies and enhance overall training value.

In terms of tactical integration, no significant hindrance was reported in collaborating with the virtual entity on a collective level for communication, air-to-air, and air-to-ground combat. However, on a team level with other F-35s, effectiveness was reduced due to the virtual entity's lack of connection to the MADL network and degraded sensor capabilities, leading to uncertainty regarding its deployment. Some pilots proposed deploying the simulator as a separate F-35 formation with degraded capabilities, while others suggested using it as a fourth-generation striker or bomber, even though the PVI is still that of an F-35 aircraft.

An issue concerning environmental integration was highlighted, focusing on challenges in obtaining realistic emissions from SAMs or aircraft when virtual elements operate alongside live ones like the F-35. Live F-35s exchange data via the MADL network using real sensors, while virtual elements rely on simulated data, potentially leading to discrepancies in information and coordination, particularly evident when operating together in formations. This problem is less pronounced when operating in separate formations due to differing tasking and reduced data dependency.

3.2.4. Day-to-day-training. When asked about the current setup's value for day-to-day training, pilots expressed that it is too limited for meaningful collaboration in formation with other F-35s. However, there's value in using it for separate formations or as red air, providing enriched scenarios for live pilots and additional training stimuli for simulation operators. Although not as valuable as live sorties, it is still considered relevant training. Ultimately, in day-to-day training, the systems must be capable of incorporating virtual or constructive elements within sixty minutes or less in the event of ground aborts.

3.2.5. Alternative training systems. In comparison with the embedded training (ET) system on the F-35, pilots indicated that ET requires pre-programming and adaptability in-flight. In contrast, the LVC setup allows for real-time adjustment. The operator can fly and respond as needed, and if required, virtual and constructive elements can be relocated and configured with a new loadout. White cell is able to instantly react upon events to keep training value as high as possible. However, ET is embedded within the F-35 and can integrate with the F-35 systems. ET and a Link-16 LVC solution are complementary to each other. Both have positives and negatives and together they can augment the mission scenarios.

Live red air is considered superior in terms of environmental integration, with sensor-collected data being deemed realistic and accurate. In addition, within-visual range operations are valuable for training when live red air is present.

4. Discussion

In the forthcoming section, the focal point is on unpacking the primary findings, exploring their implications, and identifying potential directions for future research and development. This section aims to provide a broader context for understanding the significance of the study within the academic domain. The section is segmented into three subjects: (1) training value, (2) deployment and use of

LVC, and (3) integration. While the subject of integration is not directly linked to the three research question, its substantial importance was identified during the research process, warranting its inclusion. The original research questions were the following:

1. How is the training value related to the LVC setup perceived by the airborne pilots?
2. How is the training value of the exercise perceived by the pilot of the virtual entity?
3. How can an LVC environment be applied in pilot training?

The first section that comes up will address the first two research questions. The second section will serve to answer the third research question, while the third section concerns the new topic of integration. The results presented in the previous section are derived from a small sample size, thus requiring careful consideration. Other relevant research will be examined to contextualize the outcomes. In addition, further extensive research is warranted to expand the knowledge base.

As noted earlier, integration and development were more seamless than anticipated, allowing the FENIX to participate as an immature F-35 rather than as a generic fighter as initially planned. However, limitations in both the FENIX and the integration method meant it could not fully replicate an F-35 (e.g. lacking MADL datalink capability). It was never the objective of this demonstrator to fully replicate an F-35. Although participants were unaware of these limitations—making certain comments understandable with retrospect—it remains important to acknowledge and reflect on these limitations to determine whether issues prompting these comments are LVC- or simulator-related.

4.1. Training value

The research findings indicate that the simulator operator, functioning as a virtual entity, perceives significant training value. The overall experience for the sim operator was valuable, particularly in the planning process and decision-making during flight. However, certain elements are notably absent for the sim operator (e.g. MADL, experiencing G-forces). An important aspect for achieving training value is immersion. The pilot in the simulator must feel like a full member of the exercise in order to feel fully responsible for its task and to execute its task with the same commitment as in a live scenario. Immersion is defined as the technical capability of a simulator system to allow the participant to perceive the world through that system.[5] In LVC operations, technical capability extends to interoperability with other systems, including data exchange and radio networks. Although high-fidelity simulation of certain aspects like visualizing external cockpit views may not be explicitly necessary for training, incorporating such features in the simulator can greatly enhance immersion and increase pilot engagement.

Live pilots benefit from increased training value through the incorporation of LVC, as the introduction of virtual and constructive elements enhances scenario complexity, requiring intricate planning and execution of the gameplan. LVC offers a sustainable solution for integrating additional elements, avoiding overwhelming constraints of rules, regulations, and logistics. Fidelity of the LVC environment, particularly in interactions with virtual or constructive elements, is crucial for live pilots, for example training in imperfect conditions to optimize radar configurations by degrading the representation of virtual and constructive elements.[7] In the current LVC setup, everybody had a perfect representation of the virtual and constructive elements. As future LVC applications evolve, fidelity considerations remain crucial to bring the training value to the next level. The importance of fidelity in interactions becomes more pronounced with increasing interaction and involvement between live and virtual players.

The goal of this experiment was to demonstrate the proof-of-concept of LVC through Link-16 at a live exercise. In future exercise, when LVC becomes more mature and conventional, it can be beneficial to consciously allocate elements to certain task, especially when the amount of virtual and constructive elements become bigger. Pilots suggest that red air sorties often offer less training value compared to blue air sorties.[4] To optimize training effectiveness, live aircraft could primarily engage in blue air roles while virtual and constructive elements handle red air tasks, depending on scenario objectives. Also, on the blue air side some tasks may have lower training value than other. These tasks could also be performed by virtual or constructive elements.[4] Strategic resource allocation through deliberate planning ensures optimal utilization of each element, leading to enhanced exercise value and more efficient use of resources.[4,5]

In this study, training value was assessed globally, while Woltjer et al. proposed a framework linking training value to desired learning objectives (DLOs), mission types, and pilot types.[4] Although DLOs are fighter-pilot-specific, a similar framework could be adapted for other contexts or platforms, offering a targeted approach for future research on training value in LVC environments. Woltjer et al. used this framework to evaluate training value, with pilots rating their experiences in both live exercises and hypothetical LVC exercises. Participants anticipated that LVC would enhance training value most for flying complex missions, Beyond Visual Range tactics, and missile management, while having less impact on mission planning, radar handling, and deconfliction.[4] However, interviews in this study indicated that incorporating elements through LVC could significantly enhance the training value of mission planning, especially when there are insufficient live assets available to create a complex mission planning.

4.2. Deployment and use of LVC

Pilots frequently engage in supporting their peers during training or exercises, but not all support tasks hold equal training value. This applies to roles like flying red air or certain blue air tasks, and is compounded by limitations in flight hours and environmental restrictions faced by air forces. Thus, it is crucial to optimize every available training hour. By incorporating virtual or constructive aircraft in less valuable tasks, live aircraft can focus on more valuable activities, maximizing training efficiency. Essentially, LVC enables more blue air engagements and frees live aircraft from less valuable tasks.

Aronsson et al. identified several training challenges that could be mitigated through the effective deployment of LVC environments. One such challenge is the difficulty in practicing evasive maneuvers due to deconfliction restrictions during exercises.[5] LVC offers a solution by removing live aircraft, creating safe space for real-world execution of evasive maneuvers. This approach remains relevant for complex missions, as virtual and constructive aircraft can be utilized. However, a challenge arises in distinguishing between LVC elements in terms of safety, which is discussed in the following paragraph.

This study's findings suggested against integrating live and virtual elements into a single formation due to Link-16 interaction limitations. The pilots involved in this study advised against combining live and virtual elements in a single formation, as limitations could lead to negative training outcomes. Other studies reported hesitation in integrating live and virtual elements into one formation as well,[4,5] but there has been no reporting yet on hands-on experience with live and virtual elements in a single formation.

In Aronsson et al.'s study, blue air tasks assigned to virtual elements often involved simpler or weather-dependent tasks, such as laser designation for ground targets.[5] However, this study showed that the FENIX successfully performed several blue air tasks without hindering live operators, despite some deviations from procedures and less realistic situational awareness. Integrating live and virtual elements into one formation for fifth-generation aircraft like the F-35 is currently impractical. In Aronsson et al.'s research, participants allocated mixed formations of live and virtual elements when constructive elements were introduced, with the goal of maintaining human involvement in planning.[5] Investigating whether this ''human in the loop'' role could be filled by someone from the supporting training organization (white cell) would be an interesting avenue for further research.

The decision to allocate specific entity states in LVC exercises is nuanced and context-dependent. While current arguments for allocation validity lack structured approaches, there's a need for a framework breaking down training value into manageable sections. This allows investigation into how different entity states could effectively be used in each section and for various pilot types. Aronsson et al. advocated for an LVC allocator,[6] while Woltjer et al. proposed a framework incorporating DLOs, mission types, and pilot types, laying a foundation.[4] To enhance this framework, it should be further defined with specific training values derived from expectations and practical experiences, necessitating more data collection, especially hands-on experiences, to refine and expand the framework. In addition, regular updates are crucial to adapt the framework to evolving training needs and advancements in training media like simulators.

When deploying LVC with numerous virtual and constructive elements, evaluating agreements on how to use them may become necessary. A creative strategy involves using these elements dynamically as red air, swiftly removing and respawning them in varied waves and positions after elimination. Furthermore, these elements could adopt the signatures and capabilities of other aircraft, enhancing realism.

Current exercises use kill calls and time-outs to remove players from scenarios when they are eliminated. Kill calls occur when a fighter pilot achieves lethal effects on an opponent, communicated via radio to alert others and relayed by Ground-Controlled Interception to the opponent, ensuring they do not influence the scenario until regeneration. This process, reliant on communication, can feel artificial. In an LVC setting, weapon models could directly indicate shot validity, removing delays and reducing the need for extensive radio communication, though implementation would require integration into aircraft or creative Link-16 message usage.

In air-ground interactions, SAM-1 plays a crucial role, typically focusing on targeting live aircraft during exercises like Frisian Flag. In future LVC applications, it is important to consider expanding SAM-1's role to target virtual and constructive elements, potentially enriching training value while maintaining scenario realism. However, SAM-1 will need to prioritize based on DLOs and training value, which could intensify with the addition of virtual and constructive elements. Reconsidering SAM-1's task performance in LVC settings, such as dispersing tasks or utilizing constructive models for assistance, may be necessary. Constructive weapon and behavior models may support SAM-1, which is limited by available radio communication time. If LVC could be integrated into the aircraft's systems, the realism would increase significantly.

4.3. Integration

This experiment did not formulate specific research questions regarding the precise integration of virtual and constructive elements in the live environment. However, findings from this study and others emphasize the importance of considering both safety and training value perspectives in the integration process.[4–7] Challenges in differentiation between entity states on aircraft interfaces have been highlighted, with concerns about potential confusion and safety regulations. Differentiating between live and virtual elements is crucial, especially during critical moments like evasive maneuvers. However, from a training perspective, pilots indicate that interface differentiation reduces realism experiences. Potential solutions include enabling/disabling differentiation views, automatic indication based on proximity, or treating all aircraft as live. Other integration subjects to consider include virtual and constructive elements' adherence to (training) rules and agreements, efficient altitude box allocation and adherence, and visibility to other organizations like National Datalink Management Cell and Air Traffic Control. Fundamental discussions revolve around whether simulated elements should strictly adhere to live aircraft rules, considering safety, environmental concerns, and intelligence considerations. Addressing these challenges requires further discussion, hands-on experience, and research, including human factors studies in simulators to optimize integration in training scenarios.

5. Conclusion

This study has demonstrated the potential benefits of LVC environments utilizing Link-16 (e.g. additional low-cost assets in an exercise, additional training opportunities for operators), despite the tactical datalink limitations. While advancements in training datalinks are underway, the immediate applicability of LVC over Link-16 presents an intermediate solution, particularly in augmenting day-to-day training scenarios. Despite the evident advantages, technical challenges remain, such as the necessity for stable Link-16 connections and the possibility to quickly and easily add LVC to a training. Nevertheless, the successful execution of exercises like Frisian Flag instills confidence that these hurdles can be overcome, suggesting a potential reduction in the technical support required for LVC environments in routine training operations.

Looking ahead, the scalability of LVC environments for day-to-day training facilities holds promise, offering the possibility of accommodating multiple simulators and related systems (e.g. threat emitters). However, it is crucial to acknowledge that while this study focused primarily on fighter operations, broader considerations encompassing diverse contexts like helicopter operations are essential for developing comprehensive LVC training solutions applicable across entire air forces.

In reflecting on the primary training findings, several key insights emerge. The role of the simulation pilot extends beyond mere support, playing a critical role in planning and tactical decision-making processes. Live pilots emphasize that integrating virtual and constructive elements elevates scenario complexity, interconnects tasks, and enriches gameplan planning and execution. Furthermore, LVC environments streamline the allocation of live aircraft and simulators to tasks with the highest training value, ensuring that resources and logistics are optimized for more efficient training sessions.

Moving forward, the development of a consistent framework becomes imperative, ensuring optimal allocation of pilots to the most valuable training tasks across various entity states (live, virtual, constructive). This framework, informed by DLOs, mission types, and pilot types, provides a structured approach to maximize training effectiveness.[4] However, to fully leverage the potential of LVC environments, continued effort and experience are necessary to define fidelity requirements, flight safety rules, and training regulations, fostering the safe and valuable integration of LVC into training scenarios.

In conclusion, while challenges remain, the integration of LVC over Link-16 presents a viable pathway to enhance day-to-day training operations in the near term. With ongoing developments and a concerted effort to address technical hurdles, LVC environments have the potential to revolutionize training practices, enabling air forces to adapt and thrive in dynamic operational landscapes.

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References

1. Gao Y, Zhang Y, Zhou X, et al. Overview of simulation architectures supporting live virtual constructive (LVC) integrated training. In: *6th international conference on control, robotics and cybernetics (CRC)*, Shanghai, China, 9–11 October 2021.
2. Air Force Research Laboratory. Secure Live-virtual-Constructive Advanced Training Environment advanced technology demonstration. *AFRL Fight's On*, 2019, pp. 1–4, https://afresearchlab.com/wp-content/uploads/2023/03/Fights-ON-Vol-33-Winter-2019.pdf
3. Toubman A, Roessingh JJ, Van Ooijen J, et al. Modelling behavior of computer-generated forces with machine

learning techniques, The NATO Task Group Approach. In: *IEEE International Conference on Systems, Man and Cybernetics*, Budapest, 9–12 October 2016.
4. Woltjer R, Ramberg R, Artman H, et al. The future of Fighter Pilot Training? Live virtual constructive in large force exercises: perceived and expected training value. *Int J Aerosp Psychol* 2023; 31: 20–41.
5. Aronsson S, Artman H, Mitchell M, et al. A live mindset in Live Virtual Constructive simulations: a spin-up for future LVC air combat training. *J Def Model Simul Appl Methodol Technol* 2022; 20: 1–19.
6. Aronsson S, Artman H, Mitchell M, et al. LVC Allocator: aligning training value with scenario design for envisioned LVC training of fast-jet pilots. *J Def Model Simul Appl Methodol Technol* 2020; 19: 287–298.
7. Sherwood S, Neville K, Sonnenfeld N, et al. Fidelity requirements for effective Live-Virtual-Constructive Training of Navy F/A-18 Pilots: an exploratory survey study. In: *Human Factors and Ergonomics Society 59th annual meeting*, Los Angeles, CA, 26–30 October 2015.
8. Carre M. International Data Links Society, https://www.anzidlsoc.com.au/1340%20-%20S4%20-%20Live%20Virtual%20Constructive%20TDL%20Training.pdf (2018, accessed 25 February 2025).
9. Cubic Defense. Cubic awarded NAVAIR contract to provide Secure Live Virtual and Constructive Advanced Training Environment (SLATE), https://www.cubic.com/news-events/news/cubic-awarded-navair-contract-provide-secure-live-virtual-and-constructive (2024, accessed 25 February 2025).
10. Tactical Leadership Programme. Getting stronger. *TLP jumps to LVC*, https://www.tlp-info.org/getting-stronger-tlp-jumps-to-lvc/ (2021, accessed 25 February 2025).
11. Lemmers A and Petermeijer B. LVC for joint and combined air power. In: *Symposium on Emerging and Disruptive Modelling and Simulation Technologies to Transform Future Defence Capabilities*, Bath, 20-21 October 2022.
12. Petermeijer B, Thijssen D, Lubsen Z, et al. Integrating a virtual simulator in a large-scale live exercise—lessons learned regarding training and operations aspects. In: *The international training technology exhibition and conference*, London, 9–11 April 2024.
13. Lemmers A, Petermeijer B, Lubsen Z, et al. The potential of LVC for creating air power—beyond adversaries. In: *Interservicei/industry training, simulation, and education conference*, Orlando, FL, 2–6 December 2024.
14. Ministry of Defence. Frisian Flag bereidt vliegers voor op grootschalige luchtgevecht, 2023, https://www.defensie.nl/actueel/nieuws/2023/10/02/frisian-flag-bereidt-vliegers-voor-op-grootschalige-luchtgevecht

Appendix A

Instruments

Questionnaire. The questionnaire consisted of the following items:

1. Date
2. AM or PM wave
3. Call Sign
4. What was your role in the exercise?
5. While airborne, did you notice any difference between a live and virtual entity other than no visual / limited sensor information? [YES / NO]
    a. Why?
6. Did you have equal Situational Awareness on the live and virtual entities? [YES / NO]
    a. Why?
7. Did you experience any concerns / issues with safety of flight or training rules regarding or involving the virtual entity? [YES / NO]
    a. Why?
8. Was the communication with the virtual entity effective? [YES / NO / N/A]
9. Did you have effective shared L-16 Situational Awareness regarding the virtual entity? [YES / NO / N/A]
10. Did you have a perceived deconfliction problem with a virtual entity? [YES / NO / N/A]
11. Was the tactical execution of the gameplan / contracts effective with the virtual entity? [YES / NO / N/A]
12. Did you experience differences in the cockpit workload in order to collaborate with the virtual entity (versus live entities)? [YES / NO / N/A]
13. Did you have sufficient data from the virtual entity during debrief to correctly investigate Debrief Focus Point and gameplan execution? [YES / NO / N/A]
14. Was the presence of a virtual entity in this Large Force Exercise a help or hinder, and why? [HELP / HINDER]
15. How would you suggest improvements in regard to the use of virtual elements in the exercise?

Interview with live pilots

Technical implementation. For each subject below we can ask the following two questions:

- What is the effect on Training Value? [positive, unaffected, negative]
- What is the effect on Realism? [negligible, moderate, unacceptable]

1. The behavior of the virtual entity
2. The behavior of red constructive elements
3. The presentation of the virtual entity on L-16
4. The presentation of the red constructive elements on L-16
5. The absence of the virtual entity on the radar
6. The detection of red constructive elements (with L-16)
7. The impossibility to detect red constructive elements with the radar
8. The impossibility to target red constructive elements with the radar
9. The absence of the red constructive elements on the radar
10. The impossibility to detect / target red constructive elements with EO/IR systems

Use of LVC

- Was the way the V/C elements were incorporated in the scenario useful / valuable? What improvements would you suggest for scenario building? ÿ Ï Or options for future scenarios / uses?
- With continuous work the setup can be expanded and improved, but could a setup like this be useful in day-to-day training?

Interview with simulator pilot

Deepening on questionnaire items. The subjects of the questionnaire are converted to questions for the pilot of the simulator (see list below). (Almost) every question can be followed-up by the following two questions:

- ➢ What is the effect on Training Value? [positive, unaffected, negative]
- ➢ What is the effect on Realism? [negligible, moderate, unacceptable]
- What differences did you notice regarding live entities in comparison to live training?
- How did you experience the situational awareness of others in comparison to live training?
- How did you experience the safety of flight / training rules in comparison to live training?
- Did you experience any concerns / issues with safety of flight or training rules regarding or involving the virtual entity?
- How did you experience communication in comparison to live training?
- What differences did you notice regarding tactical execution of gameplan / contracts in comparison to live training?
- Did you have effective shared L-16 Situational Awareness regarding the virtual entity?
- Did you experience differences in cockpit workload in comparison to live training?
- How would you suggest improvements in regard to the use of virtual elements in the exercise?

Technical implementation. The fidelity of the simulator is important in the perceived training value. Therefore, we want to evaluate the perceived quality / fidelity of the simulator and determine what would be minimally necessary to experience significant training value (if possible). For each subject below we can ask the following two questions:

- ➢ What is the effect on Training Value? [positive, unaffected, negative]
- ➢ What is the effect on Realism? [negligible, moderate, unacceptable]
- The flight model of the CDEF
- The flight controls
- The Tactical Situation Display (sum of several systems) Link-16
  - Fire Control Radar
  - MADL
  - Electro-Optical Targeting System (EOTS)
  - Distributed Aperture System (DAS)
- The communication systems (UHF / VHF)

Use of LVC

- Was the way the V/C elements were incorporated in the scenario useful / valuable? What improvements would you suggest for scenario building?
  - Or options for future scenarios / uses?
- With continuous work the setup can be expanded and improved, but could a setup like this be useful in day-to-day training

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