Science and Technology Enablers of Live Virtual Constructive Training in the Air Domain

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Preface

Training is an essential component of military capability. In the air domain, the history of Exercise Red Flag provides an illustration of the critical role of training in enhancing war-fighter effectiveness. Red Flag evolved as a response to investigations that were conducted following the war in Vietnam. Those investigations revealed that many USAF pilots were not well prepared for some elements of real-world combat such as dissimilar aircraft tactics and potent surface-to-air threats. They also revealed that an operator's chances of survival in combat substantially grew after they had participated in about 10 missions characterized by the presence of such threats. Red Flag was conceived as a means of providing operators with their first realistic combat missions in a training environment that was relatively safe but also representative of real-world conditions. Since its inception, Red Flag has become known as the world's premier air-combat training event and the benefits of the lessons learned during Red Flag have been realized in combat operations.[1]

Live-flying exercises such as Red Flag can provide excellent learning opportunities. However, they are expensive and logistically challenging. Environmental, regulatory, and safety constraints also place limitations on the kinds of learning experiences that can be provided during live training. Simulation provides a means by which to address some of these shortcomings. Since the 1990s, significant programs of research and development across coalition nations demonstrated that similar training benefits can be obtained by connecting distributed simulation systems.[2] Large networks of simulators are now used regularly to provide complex and realistic training for air combat. Recently, attention has turned to the possibility of integrating live aircraft into simulation networks. This has led to a great deal of discussion about the importance, potential benefits, and underpinning science and technology of live-virtual-constructive (LVC) integration.

Introduction

LVC integration refers to the use of three different kinds of systems to generate operationally realistic scenarios for training and experimentation. The *live* component of an LVC federation typically includes operational platforms, real mission systems, and personnel who are trained in their use. The *virtual* component includes similarly trained personnel and human-in-the-loop simulation systems that represent the capabilities and interfaces of operational systems in a manner that affords real-time interaction. These are often referred to simply as simulators. The *constructive* components of an LVC federation are those that represent the capabilities and behavior of operational platforms, systems, personnel, or organizational units as computer-generated entities whose actions are determined by predefined scripts, rule sets, or adaptive behavioral models.[3]

With respect to training, what distinguishes LVC from concepts such as Distributed Mission Training, Distributed Mission Operations, and Mission Training through Distributed Simulation is a specific emphasis on the integration of live platforms.[4] The use of integrated live, virtual, and constructive systems for training is expected to provide a range of benefits, such as: (1) enhancing the training outcomes obtained from live flying, (2) enabling the generation of scenarios of sufficient scale and complexity to exercise fifth-generation capabilities fully,[5] (3) augmenting existing training ranges to provide electronic and cyber warfare effects, (4) better supporting the large footprints of modern sensors, networks, and weapons, and (5) allowing new platforms to be exercised in a secure environment so as not to reveal the sensitive aspects of their capability.[6]

Despite the emphasis that is typically placed on the integration of live platforms in LVC, we believe there are several reasons to question the specific utility of the live component. For example, while it is almost certainly true that some skills are best learned during live training (e.g., those relating to the physical aspects of high-G fighter maneuvers), we are not aware of any analysis demonstrating that the augmentation of live training with virtual and constructive threats or electronic, and cyber-warfare effects, for example, increases the effectiveness or efficiency of training for *those particular skills* to an extent that would justify the significant investment that would be required. Also, as the scale and complexity of exercises grow, so do the constraints on live training associated with the requirement to maintain safe aircraft separation. This can lead to artificialities in live training. Furthermore, it is not clear how any solution that would enable the generation of scenarios of sufficient scale and complexity to properly exercise fifth-generation capabilities in the live environment would not also present problems associated with revealing sensitive aspects of those capabilities. And finally, if representing cyber and electronic warfare effects and exerting influence over large geographic areas are key objectives of training, it does not necessarily follow that the integration of live platforms provides a better solution than improved virtual and constructive training capabilities.

In light of these issues, we propose a reconsideration of the emphasis that has typically been placed on live integration in LVC training for the air domain. Specifically, we propose that the benefits of integrating live, virtual, and constructive systems may not arise as a direct result of the inclusion of live platforms or the augmentation of live training per se, but rather from the additional scope that LVC integration could afford trainers to represent friendly and threat entities and effects using *whichever* kinds of systems are most useful and practical, given their desired outcomes and the resources they have at their immediate disposal.[7] This flexibility is important not just because it could enable trainers to exercise their preferences, but also because in situations characterized by resource constraints or high operational tempo, the ability to choose between live, virtual, and constructive systems could mean the difference between being able to provide high-end training and not being able to do so. This article next examines the implications of this perspective for LVC capability development.

The Role of Science and Technology

While some of the components required for LVC integration in the air domain already exist, a great deal of development will be needed to make the most of the capability.[8] Science and technology have a critical role in helping the military to realize the potential of emerging capabilities and concepts of operation such as LVC integration.[9] To effectively align science and technology support it is necessary to have some concept of how LVC technologies are likely to be used as well as how, in combination with other concepts or technologies, they could lead to new opportunities.[10]

The conceptualization of LVC integration as a means of affording greater flexibility in the design and delivery of training may assist in: (1) clarifying the role and importance of live integration, (2) defining a developmental trajectory for the capability, and (3) aligning science and technology support to capability development. This concept suggests that the goal of LVC capability development should be to provide a broad range of options for representing friendly and threat entities and effects, thereby enabling trainers to exercise maximum flexibility in tailoring the design and execution of training events to desired outcomes and available resources. In turn, this goal suggests two roles for science and technology, which are to (1) expand the range of options that are available, and (2) help inform the choices trainers make about the use of those options.

In this article, we explore the consequences of this conceptualization with a specific focus on LVC training in the air domain and with consideration for how the combination of a range of technologies could support transformations in training capability. We do this by drawing out the details of three potential use cases for LVC integration and considering the science and technology challenges each presents. Each use case builds on those preceding it in terms of the degree of flexibility it offers to trainers. These use cases are not intended to be exhaustive or mutually exclusive but by highlighting the need for a significant amount of research and development across a wide variety of disciplines, we believe they help to clarify the requirements for science and technology support and could serve as the foundation for more detailed planning.

Use Case One: Large-Scale LVC

The importance and likely impact of LVC integration for training are often thought of in terms of broadly defined future use cases that serve to illustrate how a mature capability could be employed. One such use case that we will refer to as *large-scale LVC* provides a suitable starting point because it represents a straightforward extension of existing training practices. We use the term *large-scale LVC* to refer to the use of secure, wide-area networks to connect many diverse, geographically-distributed LVC systems to bring together large numbers of personnel to participate in complex exercise scenarios.

There is little doubt of the value of preparing personnel to operate as members of a large, integrated force in complex mission environments.[11] Existing large-force employment exercises such as Pitch Black, Talisman Sabre, and Red Flag can provide valuable learning experiences. It is possible that integrating LVC elements into large exercises could enable these experiences to be delivered just as effectively, while also reducing logistical costs and enabling more complex scenarios to be generated than would be possible using live assets alone. However, even this straightforward vision of LVC integration presents many science and technology challenges.

The Science and Technology Challenges of Large-Scale LVC

Large-scale LVC represents an extension of live exercise practices that takes advantage of emerging connectivity between live, virtual, and constructive systems.

Although connectivity between virtual and constructive systems is relatively well understood, many fundamental science and technology challenges remain in relation to establishing common, interoperable, and verifiable models of the full range of modern platforms, sensors, and weapons as well as effects such as weather and cyber and electronic warfare. LVC integration presents a particularly difficult challenge in relation to the verification and validation of such models. In part this is because interactions between systems can lead to a vast number of possible overall system states and the composition of LVC federations is unlikely to be stable over extended periods of time.[12] Nevertheless, accurate modelling of friendly and adversary systems, effects, and their interactions will be a critical driver of the realism of LVC training environments and therefore development in this area represents an important science and technology challenge.

Significant science and technology challenges also exist in relation to achieving secure and reliable integration of live platforms. To link live platforms with virtual and constructive systems in the air domain, infrastructure is required both on the aircraft and on the ground. Current solutions such as the P5 Combat Training System (Cubic Global Defence) involve the use of aircraft-mounted pods which enable the transmission and receipt of real-time air-combat parameters through encrypted communication channels. While these devices provide a baseline capability, methods for handling data at multiple levels of classification, dealing with bandwidth and range limitations, and integrating synthetic data with live aircraft systems are yet to be well established.

The challenges related to classification may prove to be particularly difficult in the context of large-scale LVC because they involve issues of policy as well as technology. Integrating platforms at multiple levels of classification requires so-called cross-domain solutions to guarantee that sensitive information is not passed inappropriately between platforms of relatively high and relatively low classification. Some products of this general kind are currently available. However, existing systems can be laborious to configure and manage and they typically operate by simply blocking data. Data diodes provide an example of this approach. These devices enforce a one-way flow of information; usually from systems at a low level of classification (the "low side") to systems at a high level of classification (the "high side"). While the simplicity of this approach is appealing, it introduces something of a paradox in relation to large-scale training. By ensuring that participants on the low side see little or nothing of what takes place on the high side, sensitive information can be protected. However, the extent to which such groups can be said to be training together, or that valid lessons can be expected to emerge from their interactions, is questionable. Methods for passing useful but declassified information to the low side have been trialed. However, much remains to be done to clarify how such approaches should be managed within exercises from the perspective of balancing security, realism, and training outcomes.

Development is also required in relation to safely and effectively integrating simulated data into live aircraft systems. Since the mission systems of most live aircraft do not enable the simulation of effects relating to virtual and constructive entities on their primary sensors, current techniques used to integrate live platforms typically involve passing datalink tracks. Research and development are required to al-low on-board aircraft systems to be realistically and securely stimulated by external signals relating to virtual and constructive entities. Initiatives such as the Secure Live, Virtual and Constructive Advanced Training Environment (SLATE) project are attempting to resolve some of these issues to give live aircrew an experience similar to that which would be expected during a real battle.[13] Considerations related to safety of flight and negative learning will be critically important as these solutions develop, as will the security implications of opening gateways to aircraft sensors and mission systems.[14]

Beyond the challenges associated with the technical integration of live platforms, the large-scale LVC use case also highlights science and technology challenges related to human learning and performance. For example, as the number and diversity of exercise participants grows and as training scenarios grow in their scale and complexity, it becomes more difficult for trainers to ensure that all objectives are addressed and all learning points are identified. It is also difficult to design large-scale exercise scenarios that provide consistently beneficial training for personnel across a diverse range of operational specializations. Because of this, participants in current exercises often participate as role players or as so-called secondary training audience.[15] This can lead to the ineffective use of resources and missed opportunities for individual, team, and organizational improvement.

There are at least two points in the training development cycle that present opportunities for science and technology to help trainers extract greater benefits from large-scale LVC events.[16] The first is through advanced methods for aligning learning requirements with the design of training systems and exercise scenarios. To provide greater clarity in defining and addressing high-end training requirements, the Air Force Research Laboratory developed the Mission Essential Competencies framework (MEC).[17] MECs define the knowledge, skills, and developmental experiences required for operators to become fully combat-mission ready. MECs also characterize existing training environments and training gaps, which can help capability managers to target the investment of training resources more effectively. Emerging applications of the MECs hold promise for improving the design of large-scale training events. For example, MEC "crosswalk" methods aim to make it easier to identify and leverage opportunities for sympathetic training across different participant groups and MEC-based live-synthetic blend analyses aim to optimize the allocation of live, virtual, and constructive training assets.

The second point in the training development cycle where science and technology could have a positive impact on large-scale LVC is in the evaluation of training effectiveness and the provision of feedback. To ensure that all learning points are identified in large, complex scenarios, advanced data capture and analysis tools are required. Examples include tools for automatically identifying key mission states and state transitions in near-real-time, scoring critical mission performance parameters, and alerting exercise staff to significant occurrences as they unfold.[18] Advanced after-action review systems are also required to enable trainers to quickly and easily organize media-and-data-rich debriefs. Prototype systems of this kind have been fielded in activities like Exercise Black Skies.[19] However, science and technology challenges remain in relation to tailoring automated metrics to different training contexts, better supporting distributed debriefs, integrating information related to cyber and electronic warfare effects, and facilitating the use of training effectiveness data to guide iterative capability improvement.[20]

While large-scale LVC is likely to afford greater flexibility than existing live exercises, the scale that characterizes this use case could mean that some similar constraints will apply. For example, it may be difficult to bring large numbers of personnel and their systems together for LVC exercises due to scheduling and workload factors, even if they do not all have to travel to one location. Because of this, it may only be possible to conduct large-scale LVC exercises with approximately the same frequency as existing live exercises. Without the ability to iterate rapidly, the pace of LVC capability development is likely to be slow. Furthermore, if LVC exercises are conducted infrequently, the technology will do little to make high-end training experiences more readily available. Next we consider another use case for LVC integration that addresses some of these problems and provides even greater flexibility to trainers for choosing how to design and manage complex training events.

Use Case Two: Small-Scale LVC

A use case for LVC integration that addresses some of the practical problems associated with large-scale LVC entails the integration of LVC systems to add complexity to the training provided for a relatively small training audience. An example of this concept in the air domain could involve the use of LVC integration to present a scenario composed of a mix of virtual and constructive friendly and threat entities to a relatively small number of aircrew operating live or virtual platforms. This use case is distinct from large-scale LVC in that it emphasizes the use of LVC systems as a way to present operationally realistic scenarios, while also reducing the number of exercise participants, the ratio of role players and secondary training audience to primary training audience, and potentially the size of the exercise staff. To contrast with large-scale LVC, we will refer to this use case as *small-scale LVC*.

Because of its potential to have a smaller footprint in terms of personnel and platforms, small-scale LVC may have advantages, including: (1) a lower cost, (2) being achievable with greater frequency, and (3) enabling training to be designed in such a way that it targets the immediate learning needs of the smaller training audience. However, for the potential of this concept to be fully realized, additional science and technology challenges will need to be addressed.

The Science and Technology Challenges of Small-Scale LVC

The small-scale LVC use case relies on the use of realistic, constructive models of the behavior of friendly, neutral, and threat entities to facilitate reductions in the number of exercise staff and role players required to generate operationally-realistic scenarios. Models of this kind are often called computer-generated forces (CGF). Many existing commercial-and government-off-the-shelf CGF packages are interoperable, at least in principle, with other LVC systems through their use of standard networking protocols.[21] However, significant challenges remain to be addressed for these systems to deliver the degree of autonomy and behavioral sophistication that would be needed to substantially reduce the number of human role players while also maintaining or increasing the scale and complexity of training scenarios. This is particularly so in relation to the representations of friendly entities, which in an idealized case would demonstrate realistic tactical behaviors and also be capable of communicating and coordinating effectively with human training participants as teammates or even instructors.[22] A recent demonstration at the Google 2018 I/O Developers Conference provided a striking illustration of how advances in speech recognition and synthesis are making interaction with synthetic agents via natural language more useful and reliable.[23] However, challenges remain in the domain of modelling human decision making.

One potentially promising approach to improving the utility of CGFs involves the use of machine learning (ML) techniques to tune CGF behavior. It is possible that using ML to "train" CGFs on the basis of large numbers of simulation runs or recordings of demonstrated behavior may provide an effective adjunct to traditional approaches that involve hand-coding scripts and/or decision rules.[24] However, challenges exist in dealing with the labor-and-data-intensive nature of ML and with extending the applications of these techniques to complex task environments. Despite the positive outcomes of recent experiments in the domain of air combat,[25] most applications of ML have thus far been limited to relatively simple, constrained tasks. While the potential payoffs from science and technology in this area are high, a great deal more work is required.

If the behavioral sophistication of CGFs can be increased to the point that the replacement of large numbers of human participants is possible, this would present an opportunity to achieve gains in LVC training effectiveness through adaptive training (AT). AT refers to training strategies in which content is tailored to participants' aptitudes, learning preferences, or styles before training and adjusted in real time or at the end of each training session to reflect on-task performance.[26] There is evidence to suggest that AT is more effective than fixed training in many circumstances.[27] In current military training practice, it is the role of exercise controllers to modify scenarios based on their perception of the performance or workload of participants. However, when there are dozens or even hundreds of participants, modifications to scenarios that are made to tailor training to the requirements of some participants necessarily have an impact on others. This limits the utility of formal AT methods in large-scale settings. The small-scale LVC use case is likely to represent a more appropriate context for the application of adaptive training techniques.

AT methods that involve modifying training in real time (so-called "micro-adaptation") depend on measures of task performance as well as current and predicted future trainee states.[28] Therefore, the development of automated, near-real-time measures of operator and team state will be a key enabler of adaptive training in LVC. Promising approaches to monitoring team states in near-real time involve the capture and analysis of the dynamics of communication flows, gaze, postural regulation, and cardiac rhythms.[29] However, few of these techniques have been implemented in near-real-time or in direct support of training delivery in operationally-representative settings.

A small-scale LVC capability, incorporating solutions to the challenges described above, would provide a great scope for trainers to choose how to represent friendly and threat entities and to tailor training to required objectives and available resources. However, a way in which the scope of options could be expanded even further is captured in the third use case described below.

Use Case Three: Universal LVC

Teams are the fundamental building blocks of the military.[30] In many situations, learning to work as an effective team member during the planning and execution of complex missions is a key objective of training. In the air domain, personnel often work in close quarters with their teammates; for example, on board command-and-control platforms or in ground-based surveillance or air-traffic control roles. Much of the science and technology goal described in relation to large-and small-scale LVC above is to reduce the requirement for human role players in training. In the case of entities that are physically remote from the training audience, this can be achieved through the development of technologies such as CGFs and speech recognition and synthesis. However, for collocated team members, the processes of direct, interpersonal coordination involving visual and even tactile perception is critical. Given the conceptualization of LVC as a way of providing flexibility to trainers, it is meaningful to ask what is required to enable the substitution of collocated human teammates with realistic synthetic agents or representations of remote human participants? The answers to this question define a third use case, which we call "universal LVC."

The Science and Technology Challenges of Universal LVC

Advanced human-machine interfaces, including virtual reality, augmented reality, and haptic technologies, are likely to be key requirements for accurately representing the constellation of visual, auditory, and physical cues associated with face-to-face interpersonal coordination. While the availability of products—such as the Microsoft HoloLens and the HTC Vive—have recently made virtual and augmented reality more accessible, there remain significant challenges associated with improving the resolution, field-of-view, and portability of these devices, as well as making them comfortable and safe to use for relatively long periods of time.

In some situations, the development of haptic technology will also be required to simulate physical interactions with; synthetic teammates, representations of remote, live teammates, and shared virtual objects. Using a combination of motion tracking and force feedback to provide haptic interfaces dates back to the 1960s. However, only relatively recently have these technologies delivered useful, believable interfaces at an affordable cost.[31] An example of promising recent developments in this area is the HaptoClone system, which allows users to "touch" virtual copies of objects from adjacent workspaces.[32]

While improvements in display technologies will assist in representing remote human teammates, much more remains to be done to support realistic interactions with synthetic entities. Recently, significant progress has been made in the representation of human bodies and faces via computer graphics and in the face and body tracking technologies required to reproduce human behavior. Now synthetic avatars can mimic the behavior of human role players, more or less in real-time[33] However, long-term challenges remain in relation to taking human role players out of the loop and driving realistic avatar behavior using constructive agents.[34] Just as an accurate understanding of the performance of real sensors and weapons is necessary for simulating those systems, the processes of interpersonal coordination during learning and task execution must be well understood before it is possible to represent them accurately using synthetic entities. The research literature on team effectiveness—and particularly that on virtual teams—provides good starting points for science and technology in this area. This research highlights the multiplicity of cognitive, behavioral, and affective factors underlying team coordination processes, the importance of subtle behavioral cues in facilitating effective teamwork, and the effects that electronic media can have in disrupting those cues.[35]

If the science and technology challenges associated with supporting realistic, face-to-face interactions with virtual and constructive entities can be overcome, along with the challenges described earlier in relation to large-and small-scale LVC, the resultant capability could provide trainers with tremendous flexibility in designing and managing training. Ultimately, this could afford trainers the ability to choose to represent almost any role, platform, or system—whether friendly or adversarial, collocated or remote—using a live, virtual, or constructive entity. Training could be tailored to address a wide range of learning requirements and practical constraints and opportunities. This would represent a truly game-changing transformation in training capability. We refer to this use case—which is centered on the idea of providing maximum flexibility in the use of LVC systems for training—as *universal LVC*.

Given the relative costs of including LVC systems in training, one might imagine that if almost any option were available, it could be difficult to justify choosing some options over others (e.g., live over virtual or constructive). Nevertheless, it's probable that the integration of systems and personnel across LVC domains will likely be required for the foreseeable future. For example, it is clear that there will always be some knowledge and skills best learned in the live environment. Undoubtedly, there will always be certain learning experiences using human participants as role players that will be more effective, reliable, or realistic than using CGFs. Similarly, the lack of suitable models—of particular roles, systems, or platforms—might arise during training with joint or coalition partners, or when the development of tactics outstrips the pace at which models can be updated or validated. Or it may be desirable to bring together particular individuals to take advantage of opportunities for synergistic training, mentoring, mission rehearsal, or to build trust and cohesion within teams. In these situations, the promise of a concept like universal LVC lies not in the advantages of one particular kind of system over another, but in the flexibility that the integration of systems affords trainers to deliver the training that is needed with the resources they have at their disposal.

The universal LVC use case is admittedly ambitious. Addressing the challenges required to achieve a capability of this kind would involve a long-term, multidisciplinary science and technology effort underpinned by enduring collaborative partnerships between the military, defense research organizations, academia, and industry. Nevertheless, we believe universal LVC represents a desirable and tractable long-term objective for LVC development and a logical goal state given our premise that the key benefit of LVC integration in training is to provide flexibility in training design and delivery.

Summary and Conclusion

The use of LVC integration for training is expected to provide a range of benefits in the air domain. This article has proposed a conceptualization of LVC integration as a flexible means of designing and delivering complex training. By describing three potential use cases for LVC integration, we have identified many areas of science and technology where challenges will need to be overcome to expand the range of options available to trainers and to help inform how options are selected. While these challenges are significant, it is our hope that the analysis presented in this article may serve as the foundation for the development of more detailed LVC science and technology plans. Ultimately, LVC science and technology will be crucial for enabling the military to fully realize the transformational potential of LVC integration. ✪

Notes

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