A New VE Challenge: Immersive Experiences for Team Training

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Abstract

Just as flight simulators enable pilots to safely practice responses to emergencies, we propose an integrated research program to develop virtual environment technology for the scenario-based training of small teams of emergency responders **on foot**—police, EMSs, hazmat teams, Coast Guard, military, etc. Such training allows repeated, varied practice of even rare scenarios. For two years, we have studied this problem while preparing a grant proposal. Here we detail the component visions, the challenges of each, and some approaches.

We envision a novel physical facility in which small teams can train together in a large immersive virtual environment (VE) that visually and acoustically adapts as team members interact with each other and with autonomous agents. The large simulation area and new tracking, rendering, and display technology will enable: natural walking movements during training; inclusion of real props; and, crucially, training of teams instead of individuals**.** New team-training pedagogy and new rapid modeling and scenario generation tools will support the training. The goal is: You are there; You learn by doing, with feedback; You jell as a team by doing together.

1 Introduction and Need

1.1 Training Dismounted Teams

The VE R&D community has achieved some major milestones. We can create some remarkably effective synthetic immersive experiences for

- Single users,
- Groups of users sharing a single simulated viewpoint, whether in a CAVE or in front of a large screen,
- Operators of virtual airplanes, ships, tanks, and other vehicles, where everything within reach is really replicated, and all the virtual world is outside windows,
- Groups of single users in separate pods, seeing each other's avatars.

These achievements are widely being routinely harnessed for vehicle operator training, engineering design review, and seismic data analysis. Some people therefore think the VE problem is solved, the field matured.

It is time to climb on beyond that plateau. Frankly there is a pressing need that we cannot today effectively meet—the immersive training of dismounted teams for complex scenarios. Infantry squads are an obvious example, but by no means the only one. All over the nation, there are vexing team training problems that can be helped by the revolutionary technologies we envision—the training of emergency responders, trauma physicians, law enforcers, etc. Homeland security has substantially increased the demand for team training, the range of skills to be trained, and the uniformity and quality required, nationwide. Already most teams do some sort of simulated training. Real emergencies of any particular kind are rare, and teams can't wait for them to occur in order to acquire experience. Full live drills are very costly, hence rare, often only once or twice a year. Some scenarios are dangerous or costly, hence simulated training is the only option. VE-based training will allow teams to train on a rich array of rare events and with the frequency required to build skills. Immersive synthetic experiences can not only be effective, they promise big cost savings. The U.S. Navy estimates that aviation simulators, a mature technology, offer a benefit/cost ratio of 19 to 1 over training on airplanes. Although we propose novel technologies that will initially be costly, they will experience radical price drops as they ride on the consumer-price curve for HDTV, projectors, video cameras, computers, and game graphics cards.

1.2 Overall Vision

Our vision is to make immersive scenario-based training as effective, cost-effective, and ubiquitous for dismounted teams as it has proved to be for flight crews and ship bridge crews.

Star Trek's Holodeck is not yet in sight. But we do envision creating "magic rooms" in which multiple unencumbered team members move freely about; use real tools on real and virtual objects; see and hear realistic image-captured environments; and interact realistically by voice, sight, and touch with each other and with autonomous virtual people.

Learning science and VE technology both need revolutionary advances. Even more challenging is the system engineering required to put them together in a working system. But the goal of demonstrably effective VE-based training of dismounted teams is now within striking distance.

1.3 Overall Challenge—Why Can't We Do It Now?

Why can we not yet train **dismounted** teams with the gut-wrenching simulations that work for seated pilots? Today's technology cannot provide:

- **Multiple** interacting **immersed** participants with **personalized** full-field-of-view imagery,
- Natural **walking about** and natural **interaction** in complex virtual environments that mix real and virtual elements,
- **Easy development** of virtual environments and training scenarios.

1.4 This Vision Developed

We and our colleagues have been studying the team-training challenge for two years. In this paper we outline a Project to develop a system that would meet the societal team training need, and we define its components. For each component, we describe a **vision** of what is needed and the technical **challenges** to be overcome. For most, we also propose a technical **approach**.

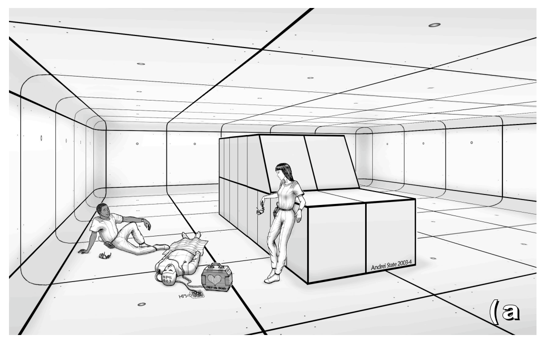
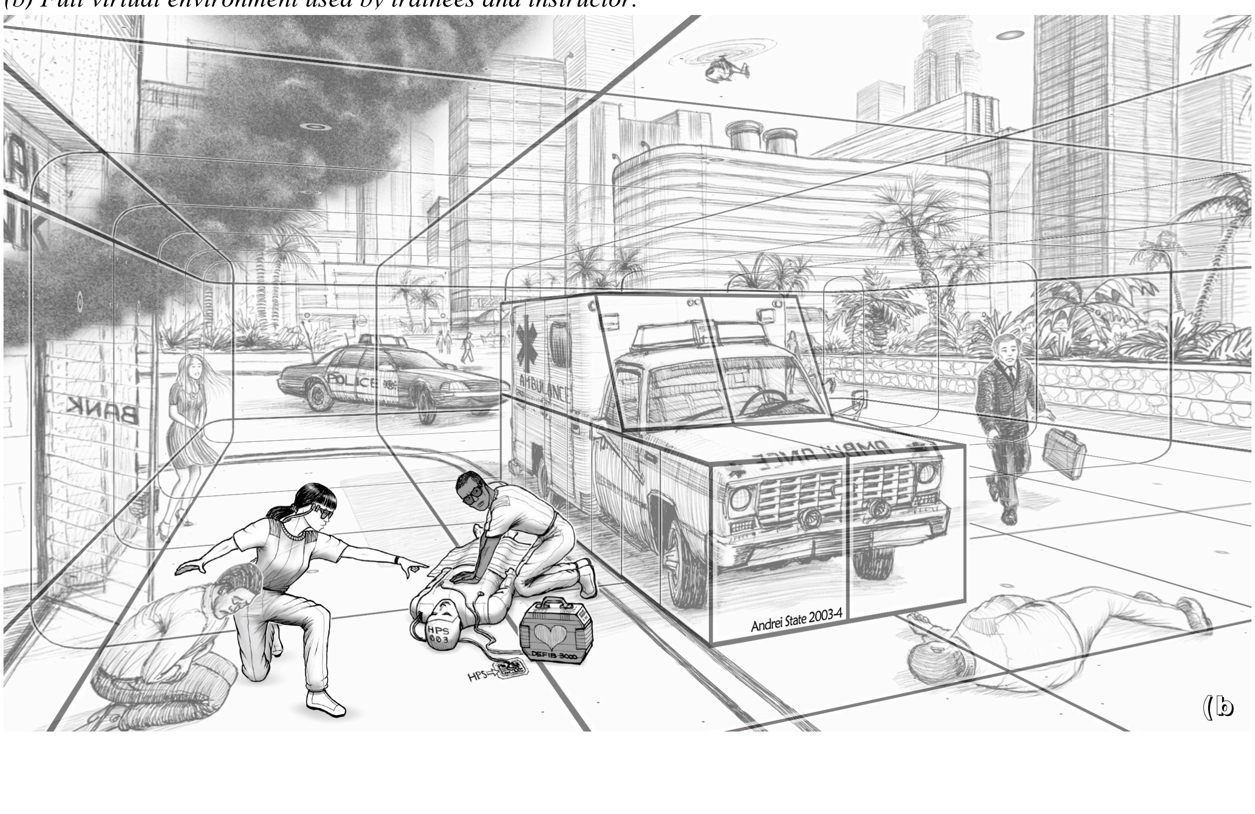


Figure 1. (a) Unlit training space with rough ambulance model. (b) Full virtual environment used by trainees and instructor.



2 Pedagogical Challenges and Opportunities

2.1 Effective Scenario-Based Training

2.1.1 Vision

Scenario-based training (SBT) relies on controlled exercises or vignettes, where the trainee is presented with cues found in the actual task environment, performs, is evaluated, and is then given feedback. SBT differs from more traditional training in that there is no separate formal curriculum; instead, *the scenarios themselves are the curriculum*. Hence scenarios must be crafted, and training executed, so that it accomplishes specified training objectives [Cannon-Bowers '98a, p. 365]. Effective SBT requires highly expert scenario authors and instructors, and they are in short supply.

Figure 2 shows the training steps developed and tested by Cannon-Bowers and colleagues for creating effective SBT. Cannon-Bowers et al. and others have demonstrated the power of SBT in several complex operational environments [Cannon-Bowers '98b; Fowlkes '98; Dwyer '99].

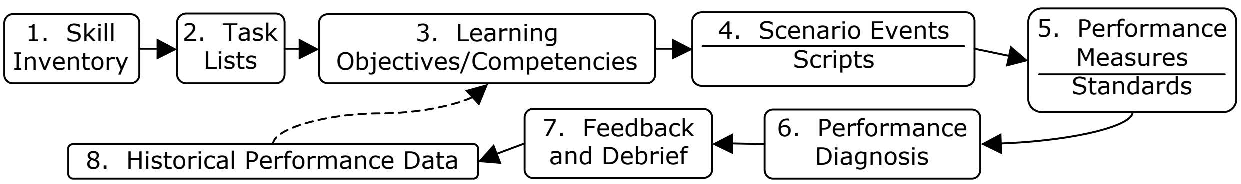


Figure 2. Components Required for Effective Scenario-Based Training

Immersive Situation-Based Training. Effectiveness in SBT depends upon the trainees behaving in training as they would in the real task. Immersive training environments undertake to simulate the real task environment as closely as practicable so as to provoke real behavior, under real stress.

Theoretical justification for immersive environments for training comes from research into how people develop expertise. Through the acquisition of domain knowledge by experience, one builds up a repertoire of instances, indexing them so that they are readily triggered by patterns of environmental cues. This has been validated in a large-scale, multi-year effort studying decision making under stress by high performance combat teams [Klein '93; Cannon-Bowers '98c].

Developing decision makers who respond quickly, and maintain situational awareness while dealing with ambiguity, requires that they be exposed to many varied instances of their task. Immersive virtual simulation can do this in a controlled, cost-effective manner. Virtual training enables teams to train on realistic tasks that would otherwise be impossible because of safety, logistics, or cost. Research in training [Cannon-Bowers '98b; Salas '00] has shown that unique benefits can be gained by using advanced interactive simulation technologies.

2.1.2 Challenge

Immersive SBT offers an immense pedagogical opportunity—automated performance assessment and feedback. The immersive system must track the participants and their actions anyway, so as to generate each participant's unique view of the action. Tracking is also necessary for calculating the interactions between real and virtual objects. As researchers learn how to compare actual motion paths to those intended in the training exercise, the Project can achieve first, automatic performance assessment, and, next, performance diagnosis enabling automatic feedback to the trainees and generation of the next training activity.

2.1.3 Approach

Adapt and test several recent learning strategies for the specific tasks of training partners:

- **Stress Exposure Training** has been shown successful in reducing trainees' subjective perception of stress, while improving performance. The effects of SET generalized to novel stressors and tasks [Driskell '98].
- **Cross training** to fill out team members' mental models of each others' jobs [Blickensderfer '98].

- **Team coordination training** teaches how to clarify roles within the team and how to improve shared situational awareness.
- **Communication training** teaches effective, empirically-derived communication patterns. It has been shown to improve performance [Bowers '98].
- **Training team leaders** to set goals, assess performance and give feedback [Tannenbaum '98].
- **Team self-correction** teaches a process and guidelines for intra-team feedback.

2.2 Cost-Effective Immersive Scenario-Based Training

2.2.1 Vision

A critical component of SBT is **frequent practice with varied scenarios.** Today the biggest cost is not equipment, nor yet trainee time, but the cost of all the other people. One recent large-scale terrorist-response exercise involved 600 trainees, but 900 trainers, observers, and extras.

Our vision is to get rid of the other people, so that a team with access to a facility can practice whenever they please, without the logistical hassle of lining up other people.

2.2.2 Challenge

To get rid of the extras, one must develop and use autonomous agents, represented by avatars.

To get rid of the trainers, one must develop automatic performance assessment and feedback generation. Along the way to this goal, semi-automatic assessment and feedback tools can help less-experienced trainers to do a good job.

2.2.3 Approaches

Synthetic forces, or autonomous agents. Many able R&D teams are working on this problem.

Semi-automated performance assessment and diagnosis. A tool must be developed that computes team behavior deviations from model-generated expected actions, and then uses these deviations to measure general and task-specific performance. These diagnoses will enable the instructor to pinpoint performance breakdowns.

Advanced behavior modeling techniques that provide dynamic representation of human performance. Expert performance models for each team role are run generatively in real time to feed "expected" behavior to both the instructor and the automated performance assessment routine. Given the state-of-the-art in cognitive modeling, it appears possible to automate the diagnosis of some aspects of team performance [Zachary '98].

Automated behavior interpretation technologies based on data from, body-tracking, eye-tracking, button-pushing, and speech. Getting behaviors from tracking data is a hard problem, currently in primitive state.

Team self-improvement. Even a pinball-machine score encourages and assists in training by iterated practice. Even the most primitive quantitative assessments will likewise drive team self-improvement.

We propose a **tool-development-driven approach** to training science, growing (i.e., iteratively developing) tools, guided and tested by the preparation of actual prototype training for and feedback from training partners. The very task of growing the tools will smoke out the deficiencies in understanding, and furnish metrics for progress.

2.3 Scenario Generation—Intelligent Scenario Authoring & Management

2.3.1 Vision

Scenario development, the most important aspect of simulation-based training, is often treated very casually. Trainees often experience simulation as "free play" events. Although enjoyable, these may yield little training. A better approach has training scenarios created by subject matter experts, typically experienced operational personnel. This approach is expensive. It can take a month to create a detailed, realistic scenario. The vision is to automate much of this.

2.3.2 Challenge

The challenge is to create a scenario generation software tool that:

- Generates valid stories and scenarios
- Is easily used by potential scenario authors, via a point-and-click interface

- Is flexible—accommodates a host of variables and input conditions
- Allows manipulation of scenario difficulty
- Is scalable for individuals, teams, and teams-plus-autonomous agents
- Is usable for many training levels—live drills, VE, tabletop exercises, classroom instruction, computer-based training, handheld computer games, and mobile telephones.
- Connects to the performance data capture tool, the feedback tool, and instructor aids
- Is easily updated and exports scripts to word processors for further customization.

2.3.3 Approach—Start with an Existing Base Product, RRLOE

Creating such a tool can leverage a public-domain work-product from aviation training. Through a partnership between the FAA and the U.S. Navy, the Rapidly Reconfigurable Line-Oriented Evaluation (RRLOE) scenario-generation software was developed at UCF to create scenarios for tests of aviation proficiency in commercial pilots [Bowers '97]. RRLOE has been delivered to over 50 aviation concerns, including every major U.S. airline. Because the RRLOE tool is generic in structure and platform, the software core can be used for other domains.

A good *event set* (set of activities that will evoke the behaviors to be trained) must target the knowledge, skills, and abilities (KSAs) defined as necessary by a stringent and structured task analysis. RRLOE strengths include its relational database that directly ties-in qualification standards, task analyses, and cross-environment standardization of terms. Thus, all authors for an environment can refer to the same KSAs.

The new environment requires important functions not presently in RRLOE:

- **Branching.** In aviation, the timeline of events for any given flight is fairly predictable, tasks proceduralized, and responses predetermined. The scenarios in the Project's driving applications need fast and conditional responses. RRLOE can create scenarios that target specific skills, but it currently does not branch on data sensed from the ongoing simulation. A research challenge is to achieve branching.
- **Real-time scenario generation.** The existing software does not run in real time as is required to avoid combinatorial explosion, once rich branching is incorporated. So, a second technical challenge is speed-up.
- **Interaction with autonomous agents.** The environments proposed have many more active agents than are currently modeled in aviation, and many of them will be (semi-) autonomous agents. The RRLOE engine must be expanded to incorporate descriptions and behavior models of autonomous agents.
- A sophisticated **training management system** that enlarges RRLOE's common relational data base to integrate every step of training track trainee exposure and progress. It must include an **integrated asset versioning system** for scenarios, captured environments, models, code, and documentation.

2.4 Automated Environment Model and Dynamic Scenario Acquisition

2.4.1 Vision

As scenarios become more complex, so do scene models. The goal is to derive content not only from CAD models, but also from a few raw images captured by camcorder, and from real-time depth images acquired by time-of-flight imaging arrays.

Dynamic 3-D capture of real or staged emergencies, including people, their surroundings, their activities, and their interactions is our ultimate vision for gathering source material for our scenario generation tools.

2.4.2 Challenge

The need is to develop a new real-time capture system suitable for large dynamic indoor and outdoor environments, deployable anywhere. More details in the next section.

2.4.3 Approach

A serious effort will be required to factor captured scenes and scenarios into their component parts, so they can be composed in new ways. Substantial authoring will still be required to prescribe articulations and animation.

3 Technology Challenges

3.1 Individualized Displays for Many Eyes

3.1.1 Vision

We are convinced that team training dictates that trainees really walk around in a synthetic environment, that they be connected wirelessly to the simulation system, that they see, hear, touch each other, that they interact with both real and virtual objects, and that they be encumbered only with the costumes and tools of their trades [Usoh '99].

This vision rules out head-mounted displays and dictates training spaces illuminated with images. The conventional CAVE™, using rear-projection, takes too much space and costs too much. Space requirements seem to dictate ceiling-mounted front-projection systems.

We envision training environments that have mixed real and virtual objects, just as theaters have real furniture and painted backdrops (Figure 1). Rather than standing in front of, or inside, rear-projection screens, the trainees will walk **around** and **through** displayed imagery effectively "painted" on the walls, floor, and real objects by compact projection systems distributed generously throughout the training environment like track lighting. With this technique one can create *passive haptic surfaces* whose combination of visual, tactile, and spatial realism will far exceed available VE systems [Insko '01]. We have used digital projectors to illuminate Styrofoam blocks arranged as walls, cabinets, and counters over a wide area [Raskar '01; Low '01]. This approach can be expanded both to support multiple simultaneous users and to incorporate additional environment-mounted cameras for closed-loop edge-blending and shadow-compensation [Jaynes '01; Sukthankar '01; Majumder '03].

3.1.2 Challenge

A major challenge is how to display a personalized view to each trainee without encumbering headgear.

3.1.3 Approach

First Generation Approach. The initial virtual training will be done with multi-user projection-based stereoscopic displays using several multiplexing approaches, including polarization, time-division multiplexing, and attention-directed selection. Such displays will require user tracking and special eyeglasses.

Second Generation Approach. Using simple fly's-eye lens arrays overlaid on a high-density emissive display substrate, it is possible to construct **true autoscopic displays,** with view-dependent pixels that effectively steer unique images directly into each eye of each VE participant. The result is visually comparable to a hologram. Only now are displays emerging with sufficient pixel density. Such displays will require no user tracking, no special eyewear, and will support any number of participants. McMillan and student have already begun to develop a prototype system [Isaksen '00]. These displays will become practical in 5-10 years, if the research is pressed now. The active circuitry at each pixel will aid in overcoming the bandwidth stresses imposed by traditional video refresh.

3.2 Real-Time Image Generation for Many Eyes

3.2.1 Vision

How to drive such displays? Graphics hardware and software have advanced astonishingly. Today's $100 3-D graphics accelerator outruns a 1995 $100,000 graphics workstation. Manocha and students have, by many algorithmic advances, achieved real-time walkthrough of 100-million-triangle models [Luebke '02; Wilson '02].

3.2.2 Challenge

However, today's graphics accelerators embody a 35-year old technology, the 3-D graphics pipeline, developed for interactive rendering from a **single point of view**. A promising alternative is a **viewer-independent** rendering architecture, to support multiple viewers from each single rendering. Such an architecture is **desirable** for the first display generation, but it is **essential** for the trackerless multi-viewer autostereoscopic display.

3.2.3 Approach

Approach. We propose a new 4-D frame-buffer architecture, which stores all viewing rays visible within a working volume, the *light field*. (The classical 2-D frame buffer stores only those rays visible from a single point.) Arbitrary views can be generated rapidly by appropriate addressing of the 4-D frame buffer. McMillan and student have already developed a feasibility prototype [Stewart '04]. This approach offers new opportunities:

- Separating rendering from view-selection decouples it from frame-rates. This enables **extremely low latency—**viewpoint changes at every scan line or pixel. It enables **higher-quality renderings**—view-change updates are no longer limited by frame time.
- It enables **rendering innovations hitherto unexploited** such as use of new rendering primitives: point-based models, image-based models, and higher-order surfaces.

3.3 Tracking—Full-Body and Other Real Objects

3.3.1 Vision

Virtual training scenarios require, at a minimum, 6-D head-pose (position and orientation) tracking for image generation, and 6-D hand, foot, and prop tracking for interaction. Tracking must be accurate, fast, robust, and unobtrusive. Whereas head-pose tracking may be obviated by autostereoscopic displays, interaction with virtual objects, including autonomous agent avatars, will always require fast limb or full-body tracking.

3.3.2 Challenge

Designing such tracking systems presents a very difficult optimization problem involving simultaneous signal processing for multiple heterogeneous devices, and dynamic models of the expected human motion. The challenge grows with the number of tracked targets. The tracking system must be small, lightweight, wireless, robust, and multi-user compatible, all over a wide area. No current solution satisfies all these requirements [Welch '02]. Our now-productized HiBall system is arguably the highest-performance wide-area system in existence [Welch '01].

3.3.3 Approach

Science. First, it is important to develop the theoretical foundations (and software tools) to enable **sensor-available-information visualization,** for the interactive exploration of candidate tracker designs. We believe hardware configuration to be the most critical tracking system decision, as **no** algorithm can compensate for poor hardware choices. We propose a mathematical tool for rapidly estimating a candidate design's performance throughout the working volume, and an interactive visualization that enables a designer to vary the hardware configuration and parameters while continuously comparing the effects. These theoretical concepts also apply to configuration and parameter optimization in image-acquisition and display, and will support similar tools there.

Technology. These tools will aid in developing novel tracking systems aimed specifically at wide-area **team** training. A distributed, body-centric, self-tracking approach seems more suitable than today's centralized systems. Individual trainee-worn systems will independently track head, limb, and prop motion in a body-relative manner [Lok '03]. New algorithms will distribute, combine, and constrain the pose estimates to ensure intra- and inter-trainee system consistency. An exciting benefit is robust high-performance tracking outdoors.

3.4 User Interaction via Responsive Virtual Physics, especially Collision Detection

3.4.1 Vision

Physics, especially dynamics, simulations in real time are crucial to the believability of virtual environments.

3.4.2 Challenge

Interaction among different entities requires real-time collision detection and contact-response computations; the user must be **actively involved with people and/or things** for effective training. The challenge is to develop:

- Interactive **collision detection algorithms** for modeling interactions among real and virtual objects, including deformable, breakable, and articulated bodies, modeled by various primitives;
- Fast simulation systems to get timely **realistic contact responses**.

3.4.3 Approach

Lin and Manocha, authors of software in world-wide use, are already pressing new methods:

- **Multiresolution** representations, **hybrid** geometric/image-based techniques, and **proximity queries** via graphics accelerators [Hoff '01];
- Automatic simplification of complex dynamical systems using **simulation levels of detail** and **multi-level acceleration** techniques [O'Brien '01; Ward '03];

- Unified, **sample-based representations** for tracking deformable surfaces, performing collision culling, and simplifying physical interaction [Hirota '99; Ehmann '00].

3.5 Environment Capture and Model Building

3.5.1 Vision

The Project envisions radically reducing the labor required to generate and specify models (geometry, textures, dynamics, lighting) for scenarios by capturing real events and disassembling them into reusable components.

3.5.2 Challenge

Whereas models of non-existent environments must be specified, extant environments can be modeled from images and range data, radically reducing cost and effort. Even non-existent environments can be composed from extant pieces. The challenge is to construct accurate and integral 3-D models from noisy image and range data.

3.5.3 Approach

The approach is based on **active sensor networks***:* a mix of pan-tilt-zoom, panoramic, fixed, and moving cameras that automatically adapt parameters to sample the targeted environment efficiently, both spatially and temporally. Projectors will complement the cameras, reducing scene ambiguity and simplifying the point correspondence problem by projecting **imperceptible structured light** [Raskar '99]; the first feasibility demonstration is working [Fuchs '04]. Time-of-flight ranging methods will also be incorporated.

The first-generation emphasis will be on developing novel algorithms for 3-D environment and event capture using active camera networks, extending and combining Pollefeys's and McMillan's work on multi-view 3-D reconstruction [Pollefeys '02], real-time stereo [Yang '03] and visual hulls [Matusik '00]. Second-generation systems will distribute computations to smart camera units for 3-D scenario capture over wireless networks. The focus will be on automatic distributed reconstruction algorithms.

The goal must go beyond today's dedicated 3-D acquisition room to capture scene and activity in the emergency room, on the street, in the boat. This will require: (1) automatic, efficient active-camera network deployment (arbitrary configurations, automated self-calibration, (2) recording of scenarios in complex spaces (occlusion, specular/dark surfaces, etc.), and (3) capturing realistic 3-D models of people [Sand '03].

Whitted has proposed a **progressive truthfulness modeling method** analogous to the progressive refinement of rendering. One builds a hierarchically ordered database of fully detailed models of houses, cars, trees, etc. The scene designer then chooses by progressively adding information about the model he wants; and the resulting model approaches his goal. But at all times, the scene has a fully detailed model of an object of the class at that node.

3.6 Sound, Speech Recognition and Generation, and Autonomous Agent Behaviors

These are essential technical components of the system we envision. We lack the experience in these areas to propose the visions, challenges, and approaches for them. Many excellent and dedicated researchers are at work.

3.7 System Integration and Iterative Refinement with Diverse Prototype Applications

3.7.1 Vision

All of the component pedagogy and technology development is for naught unless someone combines all these advances into a succession of integrated systems, each more capable, and each tested for efficacy.

3.7.2 Challenge

The challenge is to keep the several component R&D programs focused and scheduled toward the integrated systems, to put the system together, to test it with real trainers on real training, and to iteratively produce improved versions. A major challenge is keeping researchers from drifting off into blue sky territory, with pretty results that are irrelevant to building a system that actually trains effectively. An opposite challenge is ensuring that the system be applicable to more than just one narrow problem.

3.7.3 Approach

Clearly there has to be a system integrator and a Project management structure. The Project management must control the funding for the pieces, as well as that for integration and testing. Ensuring relevance demands close collaboration with real training teams who will invest their own time in sharing their expertise, defining their training objectives, and trying half-baked, and fully baked systems on their own trainees. Ensuring generality demands that the Project recruit at least two training partners with quite different training tasks. In our system-building experience, nothing matters more than continuous collaboration with diverse real-use partners [Brooks ‘96].

3.8 Providing Minimal-Investment “U-Try-It” Opportunities for Potential Adopters

3.8.1 Vision and Challenge

Trialability is one of the five characteristics of an innovation that affects its rate of adoption [Rogers 95]. Trialability for immersive team training is very low today. The cost of trying it (equipment, expertise) is too high a hurdle for all but the most highly motivated and well funded groups.

3.8.2 Approach

We propose establishing a **Facility for Immersive Team Training** (FITT), where training organizations can try out immersive experience team training in a setting where the Project provides most of the investment, both in equipment and in expert staff. RAs will serve as knowledgeable “shepherds” for visiting users.

Acknowledgements

This analysis of the problem and this vision for addressing it is the work of many people, especially:

- UNC CS colleagues: Gary Bishop, Anselmo Lastra, Ming Lin, Dinesh Manocha, Marc Pollefeys, Andrei State, Herman Towles, Leandra Vicci, Gregory Welch
- UCF colleagues: Clint Bowers, Florian Jentsch
- Training partners:
  Morehouse School of Medicine: Martha Elks, Gregory Strayhorn
  U.S. Coast Guard: CDR Tom Quiram, Don Robinson, LCDR Justin Ward
  UNC School of Medicine: Bruce Cairnes, Gregory Mears, Anthony Meyer, Judith Tintinalli

This research was funded by many agencies: Army, DARPA, DOE, FAA, NIH/NIBIB, NIH/NLM, NSF, ONR.

References

[Blickensderfer '98] Blickensderfer, E., J. Cannon-Bowers, and E. Salas, Cross-training and team performance. In [Cannon-Bowers ‘98a].

[Bowers '97] Bowers, C., F. Jentsch, D. Baker, C. Prince and E. Salas, Rapidly reconfigurable event-set based line operational evaluation scenarios. Proc. of the 41st Annual Meeting of the Human Factors and Ergonomics Soc.

[Bowers '98] Bowers, C. A., F. G. Jentsch, C. C. Braun and E. Salas, Studying communication patterns among aircrews: Implications for team training. *Human Factors* **40**: 672-679.

[Brooks ‘96] Brooks, Jr., F. P., The Computer Scientist as Toolsmith II, keynote/Newell Award address at SIGGRAPH ’94. *Communications of the ACM* (March, 1996) **39,** 3: 61-68.

[Cannon-Bowers '98a] Cannon-Bowers, J. and E. Salas, Making Decisions Under Stress:

Implications for Individual and Team Training. APA Press, Washington, D.C..

[Cannon-Bowers '98b] Cannon-Bowers, J. A., J. J. Burns, E. Salas and J. S. Pruitt, Advanced technology in decision-making training: The case of shipboard embedded training. in [Cannon-Bowers ‘98a] 365-374.

[Cannon-Bowers '98c] Cannon-Bowers, J. and E. Salas, Theoretical underpinnings. In [Cannon-Bowers ‘98a]

[Driskell '98] Driskell, J. E. and J. H. Johnston, Stress Exposure Training, In [Cannon-Bowers ‘98a]

[Dwyer '99] Dwyer, D. J., R. L. Oser, E. Salas and J. E. Fowlkes, Performance measurement in distributed environments: Initial results and implications for training. *Military Psychology* **11**: 189-215.

[Ehmann '00] Ehmann, S. and M. Lin, Accelerated Proximity Queries between Convex Polyhedra by Multi-Level Voronoi Marching. IEEE/RSJ International Conference on Intelligent Robots and Systems.

[Fowlkes '98] Fowlkes, J. E., D. J. Dwyer, R. L. Oser and E. Salas, Event-based approach to training (EBAT). *The International Journal of Aviation Psychology* **8**: 209-221.

[Fuchs '04] Fuchs, H., D. Cotting, M. Naef and M. Gross, VISLAND: Visualization with Imperceptible Structured Light for Acquisition and Non-planar Display. Currently under review (Preprints available by request).

[Hirota '99] Hirota, G., R. Maheshwari and M. Lin, Fast Volume-Preserving Free-Form Deformation using Multi-level Optimization. ACM Symposium on Solid Modeling and Applications.

[Hoff '01] Hoff, K., A. Zaferakis, M. Lin and D. Manocha, Fast and Simple 2D Geometric Proximity Queries using

Graphics Hardware. Symposium on Interactive 3D Graphics.

[Insko '01] Insko, B., M. Meehan, M. Whitton and F. P. Brooks Jr., Passive Haptics Significantly Enhances Virtual Environments. Presence Workshop.

[Isaksen '00] Isaksen, A., L. McMillan and S. Gortler, Dynamically Reparameterized Light Fields. *Proceedings of ACM SIGGRAPH.*

[Jaynes '01] Jaynes, C., S. Webb, M. Steele, M. Brown and B. Seales, Dynamic Shadow Removal from Front Projection Displays. IEEE Visualization (Vis) 2001.

[Klein '93] Klein, G. A., J. Orasanu, R. Calderwood and C. E. Zsambok, Decision making in action: Models and Methods. Ablex, Norwood, NJ, 1993.

[Lok '03] Lok, B., S. Naik, M. Whitton and F. Brooks, Incorporating Dynamic Real Objects into Virtual Environments. 2003 Symposium on Interactive 3D Graphics, Monterey, CA.

[Low '01] Low, K.-L., G. Welch, A. Lastra and H. Fuchs, Life-Sized Projector-Based Dioramas. *ACM Symposium on Virtual Reality Software and Technology*.

[Luebke '02] Luebke, D., M. Reddy, J. Cohen, A. Varshney, B. Watson and R. Huebner, Level of Detail for 3D Graphics. Morgan-Kaufmann.

[Majumder '03] Majumder, A., A Practical Framework to Achieve Perceptually Seamless Multi-Projector Displays, Ph.D. Dissertation, Computer Science, University of North Carolina at Chapel Hill.

[Matusik '00] Matusik, W., C. Buehler, R. Raskar, S. Gortler and L. McMillan, Image-Based Visual Hulls. *Proceedings of ACM SIGGRAPH.*

[O'Brien '01] O'Brien, D., S. Fisher and M. Lin, Simulation Level of Detail for Automatic Simplification of Particle System Dynamics. Computer Animation 2001.

[Pollefeys '02] Pollefeys, M. and L. V. Gool, From Images to 3D Models. *Communications of ACM* **45**(7): 50-55.

[Raskar '99] Raskar, R., M. S. Brown, R. Yang, W.-C. Chen, G. Welch, H. Towles, B. Seales and H. Fuchs, Multi-Projector Displays Using Camera-Based Registration. *Proceedings of IEEE Visualization 99*.

[Raskar '01] Raskar, R., G. Welch, K.-L. Low and D. Bandyopadhyay, Shader Lamps: Animating Real Objects With Image-Based Illumination. *Rendering Techniques 2001, Proceedings of the Eurographics Workshop.*

[Rogers '95] Rogers, E. M., Diffusion of innovations. Glencoe IL: The Free Press, 1995.

[Salas '00] Salas, E. and J. A. Cannon-Bowers, The anatomy of team training. Training and retraining: A handbook for business, industry, government, and the military. S. Tobias and J.D. Fletcher. New York, Macmillan**:** 312-335.

[Sand '03] Sand, P., L. McMillan, and J. Popovic. Continuous capture of skin deformation. *Proceedings of ACM SIGGRAPH 03,* **22,** (3): 578-586*.*

[Stewart '04] Stewart, J., E. Bennett and L. McMillan, Pixel-View: A View-Independent Graphics Architecture. Currently under review (Preprints available by request).

[Sukthankar '01] Sukthankar, R., T.-J. Cham and G. Sukthankar, Dynamic Shadow Elimination for Multi-Projector Displays. IEEE CVPR.

[Tannenbaum '98] Tannenbaum, S., K. Smith-Jentsch and S. Behson, Training team leaders to facilitate team learning and performance. In [Cannon-Bowers '98a] 247-270.

[Usoh '99] Usoh, M., K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater and F. P. Brooks, Jr., Walking>Walking-in-Place > Flying, in Virtual Environments. *Proceedings of SIGGRAPH 99,* 359-364.

[Ward '03] Ward, K., M. Lin, J. Lee, S. Fisher and D. Macri, Modeling Hair Using Level-of-Detail Representations. *Proceedings of Computer Animation and Social Agents.*

[Welch '01] Welch, G., G. Bishop, L. Vicci, S. Brumback, K. Keller and D. N. Colucci, High-Performance Wide-Area Optical Tracking:The HiBall Tracking System. *Presence, Teleoperators and Virt*. *Environments* **10**(1):1-21.

[Welch '02] Welch, G. and E. Foxlin, Motion Tracking: No Silver Bullet, but a Respectable Arsenal. *IEEE Computer Graphics and Applications*. **22:** 24-38.

[Wilson '02] Wilson, A., Spatially encoded image-space simplification for interactive walkthroughs, Ph.D. Thesis, Department of Computer Science, UNC, Chapel Hill.

[Yang '03] Yang, R. and M. Pollefeys, Multi-resolution real-time stereo on commodity graphics hardware. *Proceedings of CVPR.*

[Zachary '98] Zachary, W. W., J. M. Ryder and J. H. Hicinbothom, Cognitive task analysis and modeling of decision making in complex environments. In [Cannon-Bowers '98a] 315-344.