Integrating Video Games and Robotic Play in Physical Environments

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Abstract

Active Learning Environments with Robotic Tangibles (ALERT) are mixed reality video gaming systems that use sensors, vision systems, and robots to provide an engaging experience that may motivate hitherto underrepresented kinds of learners to become interested in game design, programming, and careers in science, technology, engineering, and mathematics. Through the use of fiducials (i.e., meaningful markers) recognized by robots through computer vision as just-in-time instructions, users engage in spatially-based programming without the encumbrances of traditional procedural programs' syntax and structure. Since humans, robots, and video environments share many inherently spatial qualities, this natural style of physical programming is particularly well suited to fostering playful interactions with mobile robots in dynamic video environments. As these systems broaden the capabilities of video game technology and human-robot interaction (HRI) they are lowering many existing barriers to integrated video-robot game development and programming. Diverse ALERT video game scenarios and applications are enabling a broad range of gamers, learners, and developers to generate and engage in their own physically interactive games.

CR Categories: Games. Video. Robotics. Collaborative and Informal Learning. Collaborative Computing. User Centered Design. Prototyping. Interactive Environments. Artificial, Augmented and Virtual Realities.

Keywords: Mobile Robots, Tangible Media, Video Games, Embodied Learning, Participatory Design.

1 Introduction: Robots and Video Games

This paper presents a new interaction and development paradigm for video-robot game development and play. Video games are becoming more and more physically interactive through the use of low-cost sensors (e.g., accelerometers) and computer vision systems. Robots, which have always been physical, are becoming affordable and ubiquitous. Likewise, robots are incorporating a greater variety of sensors and advanced computer vision systems. Most importantly, robots and mixed reality robot systems are becoming more playful! These concurrent advances are creating new synergies for the advancement of video games and novel human-robot interactions (HRI) through play and learning experiences.

Advances in the technological medium of video games have recently included the deployment of physical activity-based controller technologies, such as the Wii, and vision-based controller systems, such as Intel's Me2Cam [Intel Corporation].

The rapid deployment of millions of iRobot Roomba home robots [iRobot Corp.] and the great popularity of robotic play systems, such as LEGO Mindstorms and NXT [LEGO Group] now presents an opportunity to extend the realm of video game advances even further, into physical environments, through the direct integration of human-robot interaction techniques and architectures with video game experiences.

Over the past thirty to forty years, a synergistic evolution of robotic and video game-like programming environments, such as Turtle Logo [Papert 1980], has occurred. At the MIT Media Lab, these platforms have been advanced through the constructionist pedagogies, research, and collaborations of Seymour Papert, Marvin Minsky, Mitch Resnick, and their colleagues, leading to Logo [Logo Foundation], Star Logo [Resnick 1991], programmable Crickets and Scratch [Lifelong Kindergarten] and Lego MindStorms [Resnick 1991]. In 2000, Kids Room [Bobick et al. 2000] demonstrated that an immersive educational gaming environment with projected objects and characters in physical spaces (e.g., on the floor or walls), could involve children in highly interactive games, such as hide-and-seek. In 2004, RoBallet [Cavallo et al. 2004] advanced these constructionist activities further, blending elements of projected virtual environments with sensor systems that reacted to children dancing in a mediated physical environment. The realm of toys and robotic pets has also seen the development of a wide array of interactive technologies (e.g., Furby, Aibo, Tamagotchi) and more recently Microsoft's Barney [Microsoft Corporation 1997], which has been integrated with TV-based video content. Interactive robotic environments for education are now being extended to on-line environments, such as CMU's educational Mars rover [The Robotics Institute at CMU], and becoming popular through robotics challenges such as FIRST Robotics Competition [Center for Youth and Communities, Brandeis University, 2005], BattleBots [BattleBots], and Robot World Cup soccer tournaments [Robocup].

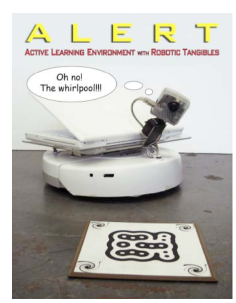

Figure 1: iRobot Create, laptop, and servo-mounted camera, observing a fiducial marker with human-legible whirlpool icons.

Video game technologies are also extending their range of impact in education through game development environments, such as Game Star Mechanics [Hayes 2007], and SMALLab [Birchfield et al. 2006] (discussed further below), in which children get to create their own games. In the LifeLong Learning and Design research group at the University of Colorado at Boulder [The Center for LifeLong Learning and Design], the constructionist activities have integrated technology with traditional crafts such as sewing and weaving. An exciting

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quality of these new gaming and programming environments, which engage users in self-motivated and collaborative gaming activities, is that girls and underserved minorities are readily adopting them [Buechley et al. 2008].

This paper presents research and development work that demonstrates a wide range of possibilities for video-robot games with a particular focus on players' physical interactions with robots and immersive video game environments. ALERT systems are supporting play, learning, programming, and end-user game design, and have been applied by users to the development of advanced video game scenarios and applications as diverse as terrain-mapping, pet-building, and Astronaut Robot Mission Simulators. These examples show that ALERT systems are suitable for a wide range of ages and skill levels, for girls and underserved minorities who have tended not to pursue Science, Technology, Engineering, and Math (STEM) topics, and for people of varied economic levels (since the systems are accessible via the Internet). Participatory design and evaluation is showing that ALERT systems can engage a new generation of gamers, learners, and developers with video games and robotics in ways that nurture intrinsic motivations.

2 System Architectures

2.1 Robotics Architecture

The core architecture of all of the scenarios and applications (see section 3 for scenarios and applications) is the robotics system architecture. The Create (produced by iRobot, which makes the popular Roomba autonomous vacuuming robot) is the foundation of that architecture. It is designed to be a relatively low-cost, user-friendly platform, programmable and physically expandable by users who are interested in robotics but may not have the time, tools, or expertise to build their own mechanical robotics foundation. Using the Create lets our research focus on programming and interactions, while also making our results highly accessible to schools, museums, and individuals who can thus apply the same technologies in their own environments.

We have equipped the iRobot Creates with cameras that enable them to "see" the physical environment. In the physical environment we use fiducials [Fig. 1] or "meaningful markers" to provide just-in-time instructions to the robots. The fiducials can be placed physically or projected onto the floor or attached to the robots [Fig. 5]. (We have also, at times, presented fiducials on PDA's, mobile phone screens, and other mobile devices that are easily carried by people and robots.) The instructions associated with each fiducial allow the Create to respond, in real time, to its dynamic environment.

In developing this system architecture we first used a MacBook laptop computer placed on the Create and used the MacBook's Camera to acquire images of the environment and fiducials. Later, desiring a more stable camera and a lighter-weight robot, we used a wireless camera to transmit the robot's view of the world to a remote MacBook or MacBook Pro. The computers, running OSX, use reacTIVision computer vision software [reacTIVision 1.3] to recognize the fiducials and their angle and position in the robot's field of view. Java software written in the Eclipse IDE then translates instructions associated with the fiducials into RoombaCom library commands [RoombaComm], which are wirelessly transmitted via Bluetooth to the Creates' Bluetooth Adapter Module (BAM).

2.2 SMALLab Architecture

The Situated Multimodal Arts Learning Lab (SMALLab; see Fig. 2) [Ref. SMALLab] is a mixed reality environment that consists of an overhead-mounted video projector, quad spatialized sound system, camera-based motion tracking engine, smart objects, and supporting software tools. The software tools support a gesture recognition engine, a system server to manage multiple simultaneous data streams, and audio and visual render engines [Birchfield et al. 2006]. Physical objects (e.g., sGlowBalls) and robots, their sensor systems, and their responsive behaviors are integrated into this system through the camera-based motion-tracking engine and through wireless communication. The SMALLab is used in conjunction with the robotics architecture (see section 2.1) to create an immersive video game environment (projected video, sound, and gaming scenarios) that incorporates users' embodied interactions with robots.

Figure 2: Robots and humans explore SMALLab's projected Mars terrain; sGlowBalls control interfaces are tracked in 3D.

2.3 Distributed Architecture

The distributed architecture for controlling on-line robotic gaming environments consists of the robotics architecture (see section 2.1) and the SMALLab architecture (see section 2.2) coupled with a server and downloadable Java applications that allow users to interact with remote physical and virtual robots, characters, and users in the SMALLab and virtual environments. The downloadable software allows users to run reacTIVision on their own machines and transmit their interactions, via TCP and UDP sockets, to control remote and/or co-located robots and video gaming elements. The simplest application that uses this architecture enables users to print fiducials to control remote robots via their own web cams.

2.4 ARMS Architecture

The Astronaut Robot Mission Simulator (ARMS) architecture leverages the robotics, SMALLab, and distributed architectures (see sections 2.1, 2.2, 2.3) and couples these with an advanced immersive planetary exploration mission environment that has been created for the study of various mission contingencies. A particular focus of these contingencies (e.g., loss of communication or power, injury, solar flare) is their impact on the optimal return of scientific data with respect to the resources expended. An Open-Scene-Graph (OSG) environment manages the immersive planetary environments and presents them to both co-located and distributed participants. The OSG environment supports multiple representations of astronauts, rovers, and ambient data within high-fidelity planetary environments. The environments that have been incorporated to date include the digital elevation model (DEM) of the Apollo 15 lunar landing site, the Jet Propulsion Laboratory's Mars Yard [Ref.], and Mount Everest. The ambient data within these environments has included the status of the astronauts and rovers, navigational trails and waypoints (including the presentation of virtual fiducials and virtual robots), projected scientific data, and various filters that enable augmented reality like visualizations of planetary environments and their features (as they relate to scientific value, safety hazards, parameters of human-robot collaboration, etc.). An OSG environment rendered within ASU's Decision Theater, a 270-degree rear-projected environment (similar to a CAVE), supports, at any given time, 25-30 co-located participants and many more distributed participants. The OSG environment has been linked, through high-resolution global positioning systems (GPS) and radar-reflection positioning systems and physiological data (e.g., heart rate and respiration), to remote participants (robots and "astronauts") at the Jet Propulsion Laboratory (JPL) and at MIT's Field and Space Robotics Lab and MIT's Manned Vehicle Lab. The ARMS architecture has also been linked to JPL's robot and planetary simulation software ROAMS and SimScape and their real-time physics and soil-dynamics modeling engines. Bi-directional communication between all participants has been realized via UDP, TCP, Skype, and Polycom video conferencing.

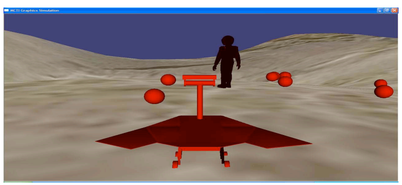

Figure 3: Remote participants' OSG view of Astronaut Robot Mission Simulator (ARMS) with navigational waypoints.

Figure 4: Co-located participants in ASU's Decision Theater interacting with ARMS's virtual Apollo 15 lunar landing site.

3 Scenarios and Applications

Through the iterative design and development and user testing of the ALERT architectures' hardware and software elements, many structured interaction scenarios and applications have been realized. Collectively, they establish a broad context of playful learning activities and meaningful human-robot interactions. These scenarios and applications make use of a wide variety of video game elements -- for example, visual elements and constructs (such as maps, multiple camera angles, or zooming) and audio elements that provide feedback for particular events or take the form of background stories and ambient sounds. These elements frequently represent a set of rules -- the game or interaction models or engagement paradigms that define the activities. ALERT scenarios and applications range from highly structured interactions with specific goals to open-ended learning experiences with multiple intrinsically motivated goals. ALERT experiences frequently involve learners in activities in which they are not only playing a game but are inventing the game, and sharing it with others as well!

3.1 Learning to "Be" a Robot

On the one hand, robotic systems can be highly engaging; on the other, they can be extremely frustrating. In order to introduce participants to some of the realities -- the great potential and the significant limitations -- of robotics, several preliminary activities have been developed. These help participants learn to deal with encumbrances – e.g., time delays in a (simulated) real setting – and introduce understandings of autonomy, avoidance of obstacles, and shared control between human and robotic inputs. Sometimes humans can override robots' actions; other times they cannot. One popular activity does not even use any technology as it engages participants in a simulated experience. A volunteer is blindfolded and the group attempts to instruct them, as if they were a remote robot, to follow a maze or simply, find a chair or corner. The participants are thereby introduced to fundamental complexities of robot control and navigation (autonomy vs. direct control, ambiguity, shared world view). Another way of getting an understanding of the robot without the effort of programming is to use the Remote Control (or simple tele-operation) to gain experience in direct manipulation and navigation. In this scenario the robot has no autonomy (or very little: iRobot Creates have cliff sensors in their wheels which are still active during remote control).

3.2 Fiducials: Meaningful Markers

The ALERT robotics architecture enables the use of fiducials for direct control. The simplest way to use the fiducials is as just-in-time instructions to the robot: users show the robot the desired fiducial precisely when they want the robot to execute the associated command. A slightly more sophisticated way of using fiducials is to place one or more in the physical environment in a location that the user anticipates the robot will traverse. Another version of this scenario is to place a series of fiducials in a sequence that instructs the robot to move from one fiducial to the next (e.g., go forward, turn right, go forward, turn left, go forward, you've encountered a whirlpool so spin and make sounds, you see a danger zone so do a u-turn, etc.). If the user wants the robot to have more autonomous behavior, fiducials may be placed in a less sequential manner. One of the most basic versions of this scenario would be to place a large ring of fiducials around a space, in effect creating a boundary, border, or fence that would "bounce" the robot around within the space. An extension of this approach could be used to create a labyrinth. A more open-ended variant would be to place fiducials in the physical environment more sparsely. When encountered, the fiducials might instruct the robot to veer away from one fiducial or set of fiducials (obstacles) and toward others, or they might elicit a behavior such as a dance or song from the robot. The placement of ambient fiducials raises the issue of perspective: a robot orientation, in which a right-turn fiducial instructs the robot to turn 90 degrees to the right, vs. a world orientation, in which a fiducial might instruct the robot to go north. Within a tracking environment, such as SMALLab or the ARMS tracking systems, the robots can readily take on either a robot orientation or a world orientation.

Since fiducials simply serve as instructions they can be extremely flexible: their use and meaning is ultimately bounded only by the creativity of the user/programmer (see section 4). Fiducials can be variously employed -- as targets for robots to follow and keep within their field of view, as "sensor" events, as x-interrupts, as new individual commands, or as sequences of procedural commands. They can be variables or variable flags (you have a key and can now unlock the treasure chest); they can elicit randomized events (go left, right, straight, or beep) or augment existing sets of procedural commands. They could even say, “When you are done with your existing commands, then ‘celebrate,’” or ”Go find another robot and ignore all other fiducials.”

3.3 Mixed Reality

The ALERT architectures create a mixed reality environment that integrates robotics play with many standard elements of video gaming experiences. The use of projected video in SMALLab [see Figure 2] and ARMS environments enables many of the standard environmental and navigational features of video games (game levels, worlds, time travel, etc.). Likewise, the audio features can be spatial, ambient, and/or synthesized by the robots. Within these rich video game environments and augmented physical spaces, “virtual fiducials” can be placed. This permits dynamic fiducials that can change in meaning and/or be repositioned either in terms of physical location or orientation. The real-time tracking systems present in the SMALLab and ARMS environments allow for multiple methods of collision detection or obstacle avoidance. One way would be to use virtual fiducials as a barrier (mentioned above); another would be to have the system keep track of the location of boundaries and objects and have it transmit this information to the robots at the appropriate time or location. In addition to the cameras on the robots, the SMALLab and ARMS environments can use their own cameras to recognize the position, location, and meaning of fiducials. These could be used not only to program the robots but to program and interact with the SMALLab and ARMS environments as well. Once the environment knows about the fiducial, it can use color-coding (e.g., green for food resources, yellow for navigational elements, red for danger or barriers) or other projected annotation to help users understand the meanings of the fiducials and environmental features. The mixed reality environment blends the virtual and physical elements (robots, humans, physical fiducials, and other physical objects). The nature of fiducials allows for low-cost replication of the icons through standard printing.

3.4 Navigation and Terrain Mapping

As discussed above, the ALERT fiducials can be used to control the ways robots navigate the space. Just as in a labyrinth scenario (discussed above), users might employ the fiducials to guide their robots through a projected or physical maze. This activity might extend to guiding robots through a domestic environment or an adventure game’s virtual environments, or to exploring a Martian crater or a lunar or planetary surface. As terrains are explored, the robots can build up an understanding of their environment and increase their navigational skill and autonomy.

3.5 Pet Building

One of the most compelling scenarios thus far, for the diverse users of the ALERT systems, has been robotic “pet-building.” This scenario adds a direct creative social component that makes the integration of video games and robots more engaging to those who may not otherwise be attracted to the stereotypical aesthetic of these technologies (e.g., DOS prompts and weapons).

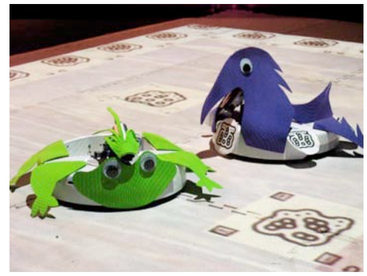

Figure 5: ALERT robotic pets, a frog and bird, with projected virtual fiducials; fiducials on the robot also facilitate interaction.

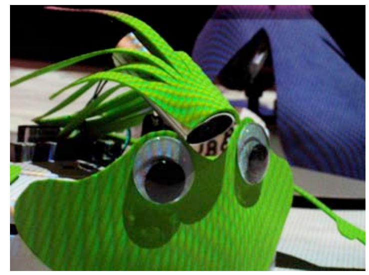

Figure 6: Close-up view of a frog-themed iRobot Create with a “camouflaged” wireless camera above the frog's eyes.

Through the combination of varied elements of the 3.1-3.4 scenarios, robots’ short- and long-term behaviors can be developed. Just as users have become engaged in the appearance of their game characters and avatars, ALERT users have become engaged in physically and virtually augmenting the “cuteness” of the robots with wiggle eyes, colorful clay, wagging tails, and projected elements in order to create pets (e.g., birds and frogs). This is also a scenario that allows for further exploration of balancing levels of autonomy – pets do not require constant direct interaction, and, likewise, they do not always pay attention to their owners. Pets can recognize their owners through sequences of interactions with their sensors, cameras, and/or through fiducials used as IDs. The tracked objects can be used as virtual leashes to “walk” or guide robotic pets through a virtual or physical environment and train the pets to do tricks and accept and react to fiducials as virtual rewards. Interactions in this realm can lead to the development of unique behavioral characteristics in the robotic pets and to elements of “social bonding” between the humans and their robotic pets [Picard 1997; Bickmore and Picard 2004]. In the near future we will be incorporating face recognition and wearable physiological sensors into the pet-building scenarios.

3.6 Multi-Robot Scenarios

ALERT’s integrated video-robot environment permits numerous multi-robot scenarios. Just as pets can be led on a virtual leash by their humans, similar leashes can enable one robot to guide another. Through the distributed architectures, multiple humans and robots can engage in physical and virtual environments. One scenario we have implemented in this domain is a robot “car” race in which a remote user can use a fiducial and its orientation as a steering wheel and interact with their robot via a web cam. In this scenario there is an opportunity to augment the physical race with virtual elements such as smoke screens. A second scenario we have implemented involves pets and humans in a virtual ecology: a frog robot and stork robot engage in a “frogger”-like game. Just as video games have different characters, different robots can have different programs—and can respond to the gaming environment in different ways, with their own personalities. For example, a parent robot might protect a child robot from cliffs and be more generous with its food. An obvious long-term goal of a multi-robot video game is swarm behaviors with multiple physical and virtual robots.

3.7 Hybrid Teams and Human-Robot Games

The ARMS architecture has been used to realize a virtual Apollo 15 lunar landing site in ASU's Decision Theater. Within this environment, virtual fiducials act as breadcrumbs representing the human and robot paths. This type of distributed physical/virtual gaming scenario can be used to explore the relative benefits of using humans and robots in planetary exploration. Similar challenges exist in the FIRST Robot Competitions, in which human-robot systems compete with one another; in human-computer chess championships; and in the Robo-World Cup in which the goal for 2050 is to have a robotic soccer team that is capable of beating a human team. In the interim it is likely that a hybrid human-robot team (and possibly even an official Hybrid Human-Robot Robo-World Cup category) will be necessary to explore the relative merits of the human and robot players. The ARMS architecture is an initial example of a system that is geared toward elucidating the respective contributions of humans and robots in hybrid systems. Another feature of the distributed systems is the ability to deploy massively multi-player games. In spring 2008, Arizona State University hosted 20 youth from the Chinese Youth Space Academy and engaged them in ALERT space exploration scenarios. These 20 students were selected from over 12,000 applicants. The sheer magnitude of the interest in space exploration and technology shows the immediate need for greater access to educational experiences through on-line and distributed interfaces. LEGO Group and NASA are both interested in the potential of on-line distributed learning environments, and we are involving each of them in ALERT space exploration scenarios. ALERT systems are also being prepared for deployment in interactive exhibits at the Exploratorium in San Francisco.

4 Iterative Participatory Design

This research pursued an iterative user-centered participatory design methodology to advance and evaluate the ALERT scenarios and applications. This process advanced understanding of the opportunities for seamless integration of video games with novel HRI techniques. The ALERT system architectures and the scenarios and applications have been developed and tested in the following settings: ASU's Sally Ride Festival, geared to promote women in science; two user studies within ASU's Active Learning in Mediated Environments course; with two sisters ages 9 and 11 in two separate 2-hour sessions; at ASU's Science & Technology Fair; and at the Phoenix Do It Yourself hackers forum, affiliated with Make Magazine; and participants in the ARMS events.

Sally Ride Festival: The Sally Ride Festival, an event for middle-school students and their younger siblings, with the goal of inspiring girls to pursue education and careers in science and technology, gave us an opportunity to share our system with a large and enthusiastic audience. The participants were curious and very comfortable interacting with the technology. To provide an engaging terrain mapping theme, we used a large plastic poster (provided by ASU's Mars Education Program) with a section of the surface of Mars printed onto it as the terrain for the robots to navigate. This poster served well to confine our exhibition area, but drew little attention from the children. They were much more interested in exploring the instantaneous responses provided by the real-time programming and control of the robot through the fiducials.

An important finding from this event was that the system appealed to both boys and girls and to children and adults. An interesting (and at times amusing) observation was that the technology seemed more puzzling to some of the parents than to their children. The children we asked were able to make the connection that the camera on the robot saw the fiducial markers and could interpret the fiducials as commands or pieces of information, much like barcodes in a supermarket. In contrast, one of the parents was suspicious of the system and did not believe that the robot was able to retrieve information from the icons, but rather felt that the whole interaction was staged -- that the presenters were remote-controlling the behaviors of the robot in response to the fiducials and children. To the parent, being able to communicate with a robot in this informal manner, by simply showing it a sheet of paper with a cookie-like print on it, just seemed too good to be true; as Arthur C. Clarke's 3rd law says, "any sufficiently advanced technology is indistinguishable from magic." [Clarke 1984] That the fiducial interactions did not faze the children might indicate that they are ready to accept the "magic" of this "sufficiently advanced technology". Consistent with Alan Kay's famous dictum that "technology is everything that was invented after you were born," the children see the "magic" of video pattern recognition and robotics and their integration as a natural part of their everyday play patterns.

Two sisters: The Sally Ride Festival led to additional user-testing opportunities. We met two sisters, a pair of middle-school girls ages 9 and 11 (and their mom), who volunteered for two subsequent 2-hour play sessions. The sisters participated in ASU's Active Learning in Mediated Environments class presentation. This session focused mainly on terrain mapping and navigation, getting the robot from point A to B within the SMALLab environment (see above). The girls exhibited intuitive understanding of the system as long as they were allowed to engage in just-in-time programming. They found pre-planning the robot's path, by placing fiducials throughout a projected maze environment, to be somewhat less intuitive but nonetheless a highly engaging challenge. Through this user session we also began to identify which of the fiducials' human-legible icons [Figure 1.] (e.g., whirlpools, u-turn, left turn, right turn, key, lock) were intuitive and which needed to be improved. A second session with these sisters explored "pet-building" scenarios and aspects of human-robot relationships in this context. To enhance the plot of the projected video game scenario, the research team had, prior to the second session, equipped the robots with physical costumes, which depicted them as a frog and a bird. The girls greeted this change with great enthusiasm; they were eager to start playing with the animals right away. One sister said, "I thought it was just a robot with a laptop on it – but it's not!" Throughout this session, the robots were no longer referred to as robots, but as "Froggy" and "Birdy." They had become integral physical characters in the hybrid video-robot game.

Science & Technology Fair: A second user-testing opportunity that emerged from the Sally Ride Festival was an invitation to present at ASU's Science & Technology Fair. Users did the placement of fiducials and operated a co-located steering wheel application. The interaction of some robots that only responded to fiducials and others that had combined steering wheel / fiducial control demonstrated that game scenarios can incorporate varying levels of autonomy and human control. During this session one participant suggested we add facial recognition software to the system. We are actively engaged in integrating not only facial expression software but wearable skin conductance sensors to enable the ALERT system to recognize and respond to elements of users' emotional states [Burleson and Picard 2007].

Active Learning in Mediated Environments: Most of the ALERT scenarios and applications were tested within ASU's Active Learning in Mediated Environments course, a project-based design course within which much of the ALERT system was developed. Eight to ten students and teachers ranging in age from 19 to ~50 used the system during these sessions. They were initially a little more hesitant than the children in our user studies to interact with the system. However, after the first few tries they became very enthusiastic and engaged fully in all of the diverse scenarios and applications that the system affords. In one interaction, robotic sounds were added to the scenario: the robot was babbling to itself as it moved through the maze. This experience led to some thrilled interpretations like, "Oh, it's talking!"

Phoenix DIY: Throughout the user testing we found that innovation frequently involved combining existing technologies in novel ways. The hacker world, exemplified by *Make* magazine, illustrates that this form of technology development can be very accessible to a broad audience of non-traditional engineers. As part of our testing and development process, we demonstrated our system to ~20 members of the Phoenix Do It Yourself (DIY) group, an organization initially spawned from the *Make* and *Craft* magazine blogs. Within this forum, participatory design activities led to the implementation of a wide range of ALERT ideas, scenarios, and applications. At this three-hour session, some small groups undertook a programming exercise to realize a PONG-like game that resulted in the exploration of playful "angle of incidence/refraction" behaviors, demonstrating not only the traditional reciprocal angles, but mischievous abnormal angles as well, such as negative angles of incidence/refraction. Others engaged in diverse pet-building and social (robot-to-robot) scenarios, including prototyping "bee-like dancing behaviors" to communicate a robot's prior navigational history or intended future path. They even speculated on the ability of a robot to lie to another robot about its intentions. Another exciting development was the demonstration of the use of multiple co-planar fiducials (i.e., printed on the same piece of paper) within the camera's field of view to determine a distance map of the fiducials from the robot. Among many other uses, this ability could be used by the steering wheel applications as a throttle adjustment, making the robot go faster when the wheel was closer to the camera and slower when it was moved away.

Astronaut Robot Mission Simulator: Many components of the ARMS architecture were developed and are continuing to be refined as part of a JPL-ASU-MIT Strategic University Research Partnership grant which fostered a collaboration between two undergraduate courses at ASU: "Engineering Systems and Experimental Design," offered by the School of Earth and Space Exploration, and Computer Science and Engineering's "Senior Capstone Project" course. As noted in sections 2.4 and 3.7, these scenarios involve co-located and distributed participants at JPL, ASU, and MIT. We have had over 30 participants distributed across these locations, controlling robots, monitoring astronaut physiology, conducting scientific analysis, etc. Through ongoing simulations and development cycles, the use of the Decision Theater as an immersive environment, coupled with information from remote participants in simulated planetary environments, is creating a next-generation gaming experience that is blending real-world and virtual spaces and applying them to learning, team work, and real-world scientific planetary exploration.

5 ALERT Discussions

The implications and future applications of systems that combine video gaming technology with human-robot interactions, such as the ones we have described, are extensive. This section presents an overview of the experiential and educational qualities of these systems. In particular, it focuses on the potentials of the ALERT systems' scenarios and applications and iterative participatory design process, as they relate to educational objectives of research on video-robot gaming synergies.

5.1 Mixed Reality Gaming

The integration of robotic elements and video game environments produces a mixed reality system (as detailed in section 2). This synthesis of physical and virtual environments creates opportunities unavailable in either environment by itself. For example, objects in the physical world cannot simply appear or disappear with no physical cause, but a virtual object can be arbitrarily generated and destroyed. If a physical object, such as a robot with a camera and computer vision system, can detect such a virtual object, then a dynamic virtual environment can affect the physical behavior of the robot. Physical objects, such as a robot, can do things that a virtual object cannot directly do, such as push other physical objects around. Combining these ideas, one might have a virtual object stimulating a robot to move another physical object, which might in turn have some effect on the virtual components of this environment. The ability to bounce back and forth between the physical and the virtual, providing links between the two and enjoying the advantages of both, establishes an engaging space with rich creative possibilities. An important feature of the ALERT system is the ease with which environments can be created and altered by the users. Fiducial markers can be boundaries, dangers, prizes, tools, or other such interactive elements. Changing the arrangement of any of these fiducials can alter the game. Walls can be built up and torn down; robots can be set to patrol circuits. The scenarios we have described are stories and background concepts suggesting the interactions that can take place. Users can take charge of these scenarios and switch seamlessly back and forth between the roles of game players and game creators.

Storytelling and character development is another important function that the ALERT system aids. The system enables multiple methods (discussed in section 4) for development of characters by 1) customizing the physical appearance of the robots, 2) attaching fiducial markers to them that will affect the behavior of other robots, and 3) by directly changing the programming of the robot. We are actively engaged in expanding the range of available forms of interactions by exploiting additional sensing capabilities of the robot, including bump sensors, cliff sensors, wheel drop sensors, and IR remote sensing, and by expanding the architectures discussed in section 2.2 (e.g., with facial recognition and physiological sensors).

5.2 Mixed Reality Gaming for Education

The applicability of these technologies to educational environments is a primary motivation for our development of these systems. The interactive experience of dynamically programming robots and game environments by physically configuring environments with meaningful symbols is one that engages students who might not otherwise be drawn to traditional programming or logic problems. Our system can change the way students perceive engineering tasks, revealing engineering as the creative endeavor that it is. Our vision is to have students engaged in problem solving, logical thinking, testing, and other engineering activities as a form of play before the labels of math, science, or engineering are applied.

There are important reasons to promote the development of future scientists and engineers and general technological literacy. Our knowledge-based economy is driven by technology innovation; many societal problems require technological solutions, and people require at least a basic fluency with technology to thrive in the world as it continues to evolve. STEM (Science, Technology, Engineering and Mathematics) learning is vital for all students, not just those who are naturally attracted to these topics in the ways they are frequently presented in schools today. We are particularly excited by the potential to positively impact girls and underserved minorities by providing a low-skill entrance level and initial success experiences in an environment that allows them to develop their STEM skills via multi-sensory learning.

Despite the importance of engineering and related fields to the economic growth of the United States, there is evidence of declining interest and abilities in these fields. For example, enrollment in engineering programs has been steadily declining in recent years. Attempts have been made to counteract this trend by implementing standardized testing in schools, lowering enrollment standards in engineering colleges, and eliminating arts programs in favor of more math and science classes; yet the negative trend continues. Recently, programs such as FIRST (For Inspiration and Recognition of Science and Technology), whose mission includes the goals "To create a world where science and technology are celebrated and where young people dream of becoming science and technology heroes" [Kamen], have been very successful in energizing kids to see engineering as a competitive, collaborative sports activity. The success of this approach is documented in a study of FIRST Robotics Competition participants [Center for Youth and Communities, Brandeis University].

5.3 Active, Engaged, and Alert Learners

Engaging subject matter promotes learning. Gaining and holding the attention of students in today's classrooms can be difficult. For students lacking experience with, or doubting their capacity in, a given subject, this problem is amplified. One way to make a subject inviting for these students is to provide a "low floor" (a point of entry that is simple and intuitive) [Resnick 1991]. Our system provides this low floor through the natural just-in-time programming enabled by the fiducials (as described in sections 2.1 and 3.1-3.7). The storylines and themes established by the participants and appealing scenarios and applications serve to maintain interest in the learning experiences offered by the ALERT system. The multimodal interactions and feedback provided by this system create a dynamic user experience with multiple channels for information transmission, serving diverse thinking and learning styles [Gardner 1983]. These channels include audio and video feedback, kinesthetic experiences through the use of tangible interfaces, and verbal communications between users.

Our system is intended to engage students on multiple levels. At its basic level (the "low floor"), it provides problem solving and competitive games that require logical thinking and spatial reasoning skills. At a medium level, it offers the opportunity for students to create their own games and challenges, using the system as it already exists. This requires more creative thinking and a deeper understanding of the tools we've created. At a still higher level, revealing the high ceiling of the project, students can delve into the design and programming of the individual technology components that make up the system, altering and expanding on what we've provided. Students enter the system enjoying the seemingly magical control over the robots' actions through communicating commands by showing the robots printed images (the fiducial markers), but eventually want to understand how to perform the magic trick – how to do the programming that makes the system work.

Just as games can start off being easy (so as not to immediately frustrate players) but gradually become more challenging (so as to remain engaging as the players' skills improve), a learning system should be dynamic and adaptable in order to maintain its effectiveness as a teaching tool. One of the strengths of our system is its flexibility. It functions as an open-ended learning environment in which students can freely play, explore, invent, and evolve understandings of space, timing, logic, interrelations, and dependencies. In certain scenarios ALERT systems can also aid learning of specific directed lessons, such as a geometry problem illustrating the Pythagorean theorem. Students show an enthusiastic willingness to combine multiple scenarios and approaches when working with and designing robots and robot-robot or video-robot interactions. We've observed these self-motivated and largely self-directed creative activities to be a promising way to generate a wide diversity of hybrid video-robotic games.

Throughout this participatory design and development process, emergent behaviors frequently occur in the system, suggesting new games and learning activities, including puzzles, hide-and-seek (and other robotic implementations of traditional children's games), and artistic applications (such as dancing). To date we are capturing these ideas and using them to develop and refine additional scenarios and applications.

6 Conclusions

The ALERT system and the iterative participatory design, development, and evaluation described in this paper represent the evolution of, and contributions to, a new spatial paradigm for advancing video game technologies, human-robot interactions, and embodied educational experiences, in physical environments. The diverse systems, scenarios, and applications presented here show the significant potential afforded by integrating robots and video games through the use of tangible fiducial interactions. Within the ALERT system, human-robot interactions and programming experiences can be made accessible to users with no traditional programming experience by simply leveraging their preexisting logical thinking abilities and experience with everyday programming examples such as street signs (stop, go, speed limit, right turn). Since humans, robots, and video environments share many inherently spatial qualities, this natural style of physical programming is particularly well suited to fostering playful interactions with mobile robots in dynamic video environments. The low floor of this system makes experiences with technology easy and exciting and opens up STEM learning experiences to those individuals who are typically not drawn to these subjects. The ALERT scenarios and applications are enabling a very broad range of gamers, learners, and developers to generate and engage in their own physically interactive games. The attractive qualities of video games, including interesting characters, storylines, and multi-sensory feedback mechanisms, combined with the physically active involvement promoted by robotic elements and tangible fiducials, are resulting in systems that broaden the capabilities of video game technology and human-robot interaction.

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