Imperfect Robot Control in a Mixed Reality Game to Teach Hybrid Human-Robot Team Coordination

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Abstract
A key component of team coordination in real-world practice involves communication and work execution from multiple perspectives; this is especially true for unmanned robotic system operators. Previously, such communication skills have been challenging to train, requiring many users and/or high-fidelity simulations. The present research develops a mixed reality game using a small robot and alternate roles to engage two players in team communication through information distribution. The robot features imperfect controls, creating challenge and reflecting the real-world context. This paper presents the game design and development challenges, reflecting on the value of mixed reality for training hybrid human-robot teams.

Author Keywords
Mixed reality, game design, team coordination, hybrid human-robot teams.

ACM Classification Keywords
H.5.3 [Group and Organization Interfaces]: Computer-supported cooperative play.

Introduction
Due to the complexity of work, teams are required in many domains; team coordination skills are critical to the

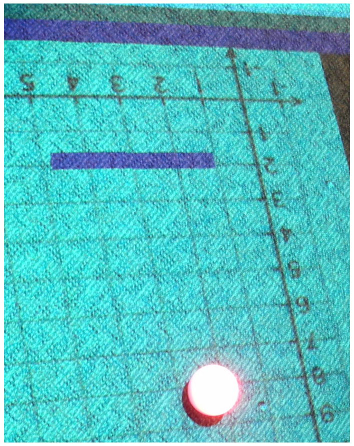

Figure 1: A physical robot (red orb) being run in a projected virtual world on the floor in *MRMaze*. A blue obstacle appears near the top; the grid on the floor supports communication.

Figure 2: The Sphero robot set to the red color necessary for tracking.

successful functioning of such teams [9, 12]. As technology proliferates, the need for human-human interaction remains essential. This is especially true when piloting unmanned robotic systems, used in multiple domains where a pilot and other team members must communicate about the robot and its environment [8]. Training communication skills either happens in the field, with real consequences to failure, or in large, costly simulations [13]. To engage players in team coordination, we build on our prior guidelines of alternative roles and information distribution [13], developing new guidelines about imperfect control of a robot for hybrid human-robot team contexts.

Through the present research game, *Mixed Reality Maze* (*MRMaze*), we seek to support team coordination learning in dyads. In the game, a *robot operator* imperfectly drives a simple robot through a maze projected on the floor with missing information. A *map commander* supports the operator by communicating about information available only to him/her. By using information distribution and alternative roles to make players interdependent on one another, combined with a robot that moves imperfectly, we aim to create a risk-free environment in which to build the team coordination skills.

In this paper, we discuss background, followed by an early version of the *MRMaze* design at a high level, then delve into the technical implementation. We close with challenges discovered in the game development, to support mixed reality game designers; we reflect on the value of mixed reality for education; and describe future work.

Background

Team Coordination Simulations and Zero-Fidelity

Prior educational simulations support team coordination learning, yet require many users or focus on high-fidelity details of the real-world environment, rather than team coordination [1, 10]. High fidelity is expensive and not necessarily required for success [7]. We develop *zero-fidelity* simulations [13] that eschew the real-world environment and focus on the human-centered components of practice, reducing cost. The simulation is thus focused on how players interact with one another around information, rather than the original physical context (providing a zero-fidelity re-creation).

Mixed Reality

Mixed reality systems combine the real world and a virtual world using sensors and databases [3]. Often, a virtual world augmenting the real one, connecting in an isomorphic way. Prior research has identified the need for *seamful design* that incorporates inherent characteristics of mixed reality technologies, including failings and/or inconsistencies, as a purposeful part of the design [2, 4]. The present research leverages the technological characteristics of the robot as a component of design.

Game Concept

The present research develops a small-scale, two-person mixed reality game that engages human-robot team members in processes of team coordination. The success of this design hinges on developing an environment in which players have a shared goal, but distinct, interdependent roles and distributed information. Further, real-world robots are piloted imperfectly, needing to respond to changes in the environment (such as gusts of wind for aerial systems or uneven terrain for ground systems). We thus import the challenge of imperfect

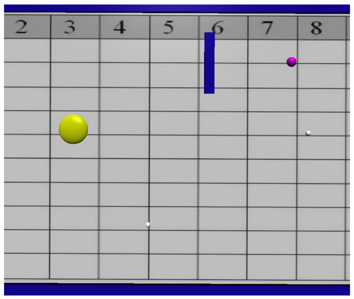

Figure 3: Robot operator's view: only the blue obstacle is visible (but not the yellow one), along with the white and purple collectables. The yellow circle is the placeholder for the robot. Figure 4 shows the matching map commander view.

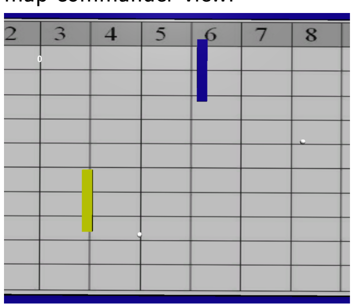

Figure 4: Map commander's view: both the blue and yellow obstacles are visible, along with the white collectables (but not the purple one). Figure 3 shows the matching robot operator view.

control into gameplay. We immerse players in a scenario where communication is necessary to succeed. The ultimate goal behind the game is to expose the players to this unique type of communication through a fun medium. Figure 1 shows the game in action.

In *MRMaze*, a virtual game world is projected on the ground that *excludes* some obstacles. One player, the *robot operator*, drives a rolling, spherical robot, a Sphero [15] (Figure 2), avoiding visible and *invisible* obstacles (Figure 3 shows an example). Using computer vision, the game system determines when the Sphero robot collides with obstacles. The other player, the *map commander*, observes a separate visualization (Figure 4) of the game and communicates with the robot operator. The two must work together, from these alternative perspectives, to win the game.

The present research builds on our *Team Coordination Game* project, developing a two-player game to engage players in communication while working in a human-robot team context. It leverages the prior design implications of using alternative roles and information distribution, adding the uncertainty of an imperfectly controlled robot.

Alternative Roles
The game features two distinct roles: the robot operator and the map commander. The robot operator's role is to pilot the Sphero, avoiding enemies and acquiring collectables to increase the team's score. The robot operator uses the default Sphero app [11], which allows the robot to be driven with a virtual analog stick.

The map commander's job is to warn the robot operator of upcoming obstacles, which the operator cannot see. The obstacles gradually increase in speed, requiring the two player's communication to be quick and effective.

Information Distribution
Not all information is available to both players. The map commander is able to observe more details in the game world than the sphere driver can, in order to encourage communication between the two players. Figures 3 and 4 compare the two perspectives.

The map commander is able to see incoming obstacles which, if collided with, will end the game. The robot operator does not have access to this information, and is therefore dependent on the map commander to communicate. In addition, these obstacles move towards the player at a quicker and quicker pace, making proper communication time-sensitive. This way we foster an environment where not only is communication necessary, but also must be done quickly, as in many real world scenarios.

Imperfect Robot Control
The Sphero robot used in *MRMaze* drives imperfectly, a fact we leverage to enhance the value of the simulation as a way of capturing the real-world experience of operating a robot. While prior work has sought to improve the control of such robots by using more intuitive controls in *Sphero Sumo* [5], the present work aims to leverage the challenges in controlling the robot. The Sphero takes time to accelerate and decelerate, and its turn radius is large. Further, the projected game map is not large (approximately 2 meters $\times$ 1.5 meters). As in *Sphero Sumo*, bumpers around its edges prevent the robot from leaving the game board.

Technical Implementation
MRMaze combines a number of technologies to create a coherent mixed reality game. In addition to the Sphero robot and its smartphone app, we use a projector and

Figure 5: Free-standing wooden frame for holding projector and webcam.

Figure 6: Projector and webcam in custom mount on frame.

webcam attached to an overhead mount to produce the game board and gather data to track the robot. On the software side, we use the vvvv multipurpose toolkit [6] to track the robot in the video feed and use software developed in the Unity 4.0 [14] integrated game development environment to operate the game engine and render the two players' displays.

Physical movement of the Sphero robot is the simplest component, because it is handled entirely by the native Sphero Android application, Sphero Multi Drive [11]. We connect the Sphero to an Android tablet via Bluetooth; there is no communication between the Sphero application and any other part of the system. The design of the Sphero introduces the needed imperfect robot control.

One of the challenges of designing the system was that it needed to remain simple to set up and move, despite requiring substantial hardware. To meet these requirements we constructed a free standing wooden frame (Figure 5) on which to mount the projector and webcam. The projector was placed in a cloth sleeve and strapped to the frame (Figure 6), pointed at the floor. To help ensure that the webcam has a clear view of the projected area we tucked it into the projector sleeve, directly above the lens. This gave it a clear view of the play area on the floor. The setup creates an approximately 2 meter $\times$ 1.5 meter play space.

The Sphero robot lights up, with customizable coloration, so we use color tracking, with vvvv, on a webcam feed to determine its location on the game board. We use a bright red color (Figure 2), and do not use the same color in the projected game board. The tracked location is passed to the game engine, which handles placing the virtual representation of the Sphero in the appropriate place.

The game engine program, written in Unity with C# scripting, handles all the mechanics and logic of the game itself, including obstacles and collectibles; menus; and high scores. Using the location of the tracked color provided by the webcam and vvvv, we use Unity to drive the game entities and detect collisions with them. The complete game view is displayed to the map commander's laptop screen, while the obstacles are culled from the game view before being projected onto the floor for the robot operator's view.

Discussion

Based on the process of developing and testing *MRMaze*, we identify several points for mixed reality developers to consider. Our primary contribution is the use of imperfect controls for educating hybrid human-robot team members, but we also highlight how the limitations of the real world impact game design.

Seamful Design for Imperfect Controls

One interesting challenge facing the robot operator is the imperfect control system of the Sphero robot. One large difference between mixed reality and virtual reality is that in a virtual implementation control of the player avatar can be instantaneous. In such implementations, imperfections in control can be eliminated by design. In a mixed reality system, where the real world impacts play, however, the robot operator is bound by the laws of physics: the robot has a large turning radius, takes time to stop and come to full speed, and is delayed in changing directions. All of these factors must be taken into consideration by the robot operator in order to ensure success; they are learnable, but make action (and communication about action) difficult.

We take a seamful design [2, 4] approach here, making the imperfections of the Sphero a component of gameplay and mapping it to the real-world experience of operating an unmanned robotic system. Such systems have imperfect controls and are affected by the environment. The operator must learn to account for these concerns. In addition, our game design has undergone a number of iterations to make gameplay fair, most of which center around adjusting the collision detection radius for the robot and modifying game speed.

Limitations of the Real World
Another consideration is that the physical size of the play area is set, and cannot be virtually augmented the same as in purely digital games. Due to this physical constraint, the area the player can explore is severely limited. Normally, to compensate for a small screen, the designer simply scrolls the play area, creating an environment larger than the screen. With a mixed reality system the player's avatar is a physical object, and thus when it is at the edge of the play area, it is physically positioned there. The virtual world could be extended by enabling computer controls to override the robot (causing it to move slower, for example) or mapping the real world non-isomorphically to the virtual one (so that movements in the real world are not a 1:1 mapping to the virtual).

Conclusion
We have presented the design and implementation of the *Mixed Reality Maze* game to help train hybrid human-robot teams. We begin developing a new guideline for the hybrid human-robot team context: *imperfect robot control*. In the present research, we find value in the imperfect controls of the Sphero robot, developing a *seamful* design. Future work will connect more deeply into the real-world contexts of human-robot teams, iterate the design, and evaluate it with different communication modalities for operator and commander.

Future Work: Evaluation and Iteration
Design and development of the game is ongoing. The next steps in the game design will involve evaluation and iteration, as well as the inclusion of stakeholders in the human-robot team domain. We plan to develop the work by engaging with real-world robot operators to better understand their concerns in working with robots on a team. Further, we will evaluate the game to determine not only if it successfully impacts team coordination and communication skills, but also whether it functions as a successful simulation of real-world practice.

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