An Architecture for Simulating Drones in Mixed Reality Games to Explore Future Search and Rescue Scenarios

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ABSTRACT

The proliferation of unmanned aerial systems (i.e., drones) can provide great value to the future of search and rescue. However, with the increase adoption of such systems, issues around hybrid human-drone team coordination and planning will arise. To address these early challenges, we provide insights into the development of testbeds in the form of mixed reality games with simulated drones. This research presents an architecture to address challenges and opportunities in using drones for search and rescue. On this architecture, we develop a mixed reality game in which human players engage with the physical world and with gameplay that is purely virtual. We expect the architecture to be useful to a range of researchers an practitioners, forming the basis for investigating and training within this unique, new domain.

Keywords

Mixed Reality, Drones, Games, Simulations, Disaster Response, Search and Rescue.

INTRODUCTION

As unmanned aerial systems (i.e., drones) proliferate, we expect them to be of great value to the future of search and rescue (and disaster response, in general). Such devices have started to be used in disaster, often controversially, raising concerns around privacy violations and safety regulations (Wall 2013; Lidynia et al. 2017). As these scenarios materialize, there will be a need for researchers to develop and test designs, as well as for practitioners to train with them. To develop, test, and train for hybrid human-drone team scenarios in search and rescue, we expect to the following issues will arise:

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- **Team Configurations**: concerns around how best to construct cooperating teams of humans and drones to maximize effectiveness (e.g., what is the right ratio of humans and drones?, what are their roles?, what types of drones and sensor payloads are most effective?);
- **Search and Rescue Methods**: the incorporation of drones will alter how search and rescue is performed (e.g., how do we use drones to find victims?, how do we use drones to assess structural stability?, what search patterns do we employ?); and
- **Device Configurations**: attention must be paid to how to design sets of devices that enable mobility while providing sufficient control of drones (e.g., how do we best direct teams of drones?, what is safe and effective in the field?).

To address these issues, we are developing testbeds in the form of mixed reality games with simulated drones. The games are *mixed reality* because one or more humans play these games in physical reality to which a virtual reality is connected. The virtual reality contains a game scenario and one or more drones, which do not exist in the physical reality. The simulated drones operate in an existing open-source robot simulator (Gazebo[1]) (Figure 1) that can recreate a number of drone configurations and accurately simulate various sensor payloads.

The present research develops an architecture in which human players (e.g., trainees, researchers, practitioners, study participants) engage in a game that combines work in the physical world with gameplay that is purely digital. The human players are equipped with wearable computers and sensors, enabling the digital game to track their location, context, and activities. Drones are completely simulated and do not exist in the physical world, enabling developers to address the above issues without concerns about public safety due to drone mishaps or aviation rules.

In the remainder of this paper, we synthesize a brief background on disaster response and provide deeper insight into drones, games, mixed reality, wearable computers, and prior disaster response simulations. We then explain our proposed architecture that facilitates simulating drones, developing mixed reality, and collecting data. As a parallel thread, we describe our game design for exploring search and rescue drone applications; while we expect to develop multiple designs in future, we present our current version here. We then discuss the benefits and drawbacks of using mixed reality for this purpose and close with our expectations for future work.

BACKGROUND

Disaster response is a complex set of activities to mitigate the effect of a critical incident (Toups, Hamilton, et al. 2016). The term *incident* refers to "An occurrence, natural or manmade, that requires a response to protect life or property..." (U.S. Department of Homeland Security 2008, p140). *Responders* are people who contain the impact of disasters and prevent further loss of life and property. Such response is crucial, because disasters cannot be prevented entirely, but their impact can be contained and reduced. We draw on our prior research around disaster response teams (Toups and Kerne 2007; Toups, Kerne, and Hamilton 2011; Toups, Hamilton, et al. 2016) to drive the design of our mixed reality game and wearable system.

Search and rescue is a disaster response operation to locate persons who are in distress or imminent danger, aid them (e.g., medical, food), and move them to a safe place (Department of Defense 2006). There are different types of search and rescue operations (e.g., urban search and rescue (US&R)[2], mountain rescue[3]). Time is a critical factor in search and rescue operations, any delay might result in loss of the persons, therefore, using technology such as drones, in these operations could help to minimize the time needed to find persons who are in distress (Waharte and Trigoni 2010).

Drones

The term *drone* refers to an unmanned aerial vehicle (UAV) that can be controlled remotely (Chang et al. 2017; Barin et al. 2017; Jones et al. 2016), and is a subset of unmanned aircraft systems (UAS) (Austin 2010). Drones come in many sizes from micro drones (e.g., those that fit in a human palm) to large drones (e.g., military drones the size of small fighter jets). Flight type (e.g., quadcopter, hexacopter, fixed-wing) impacts what work a drone is capable of (e.g., fixed-wing cannot hover, but might be able to move quickly) (Vergouw et al. 2016). Payloads are the equipment that drones carry to perform useful work (Austin 2010). In search and rescue, payloads are various sensors (e.g., camera, thermal imager, GPS), though future scenarios might include effectors (e.g., to support delivering materials). Drones are expected to play a crucial role in search and rescue and are already involved in the

[1] http://gazebosim.org
[2] FEMA's Urban Search & Rescue page: https://www.fema.gov/urban-search-rescue
[3] Mountain Rescue Association: http://mra.org

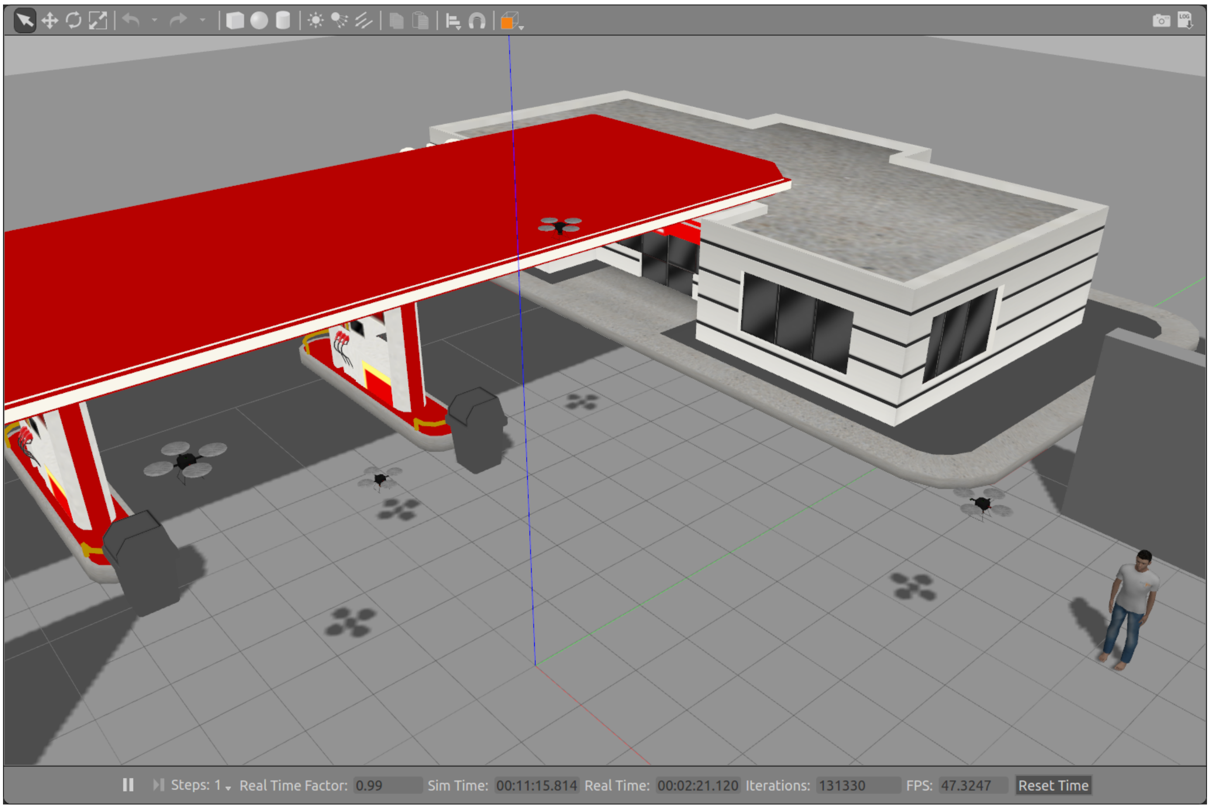

Figure 1. Multiple drones simulated in Gazebo.

field (for better or worse). For example, drones were, controversially used in search and rescue during Hurricane Harvey in summer 2017 (Hutson 2017; ABC News 2017). Drones were used to to create a 3D map of the flooding and the damage that helped first responders in rescue operations.

Mixed Reality and Wearable Computers

Systems that connect virtual and physical reality in some meaningful way through the use of networks, sensors, and databases are *mixed realities* (Milgram and Kishino 1994). These range from augmented reality, in which conformal 3D imagery is integrated with a perspective on the physical world, as with most aircraft head-up displays to augmented virtuality, in which physical-world artifacts and spaces are integrated into a virtual world (Sharma et al. 2017; Alharthi, Sharma, et al. 2018). The present research is concerned with systems between these extremes, mixed realities, in which we integrate virtual reality with physical reality without the augmented component. That is, simulated drones will be able to send data to a player in the physical world, but the player will not be able to see the drone. Later extensions of this work could include an augmented component to enhance immersion.

Wearable computers are computing devices and sensors that can be worn on the different locations of the human body to provide context-sensitive information support while working in the physical world (Barfield 2015; Mann 1997; Starner et al. 1997). Wearable computers are an enabling technology for mixed reality. Wearable devices establish a constant interaction between the user and the environment, and often form their own network of intercommunicating effectors and sensors. These devices provide a different range of affordances compared to other device types (e.g., desktops, laptops, smartphones) (Barfield 2015) owing to their form factors (e.g., smart glasses, smartwatches, smart rings), input modalities (e.g., speech commands, touch screens, air-based gestures), and output modalities (e.g., display, audio, vibration). These input and output modalities allow the user to monitor and control other devices. As these devices proliferate, we expect them to be extremely valuable in search and rescue contexts. The present research aims at creating testbeds for configurations of wearable devices in the context of working with drones.

Game Design

Games are framed as a combination of rules and play, involving designed game mechanics, through which players make choices (Salen and Zimmerman 2004). *Rules* are the structures of a game that constrain player choices, while *play* is the freedom to make choices within those constraints (Salen and Zimmerman 2004). These logical procedures or mathematical formulae frame the choices to which a player has access. Rules define the outcomes of choices, resulting in new, observable game states. To that end, play is the essential experience of the system that the rules create. The combination of rules and play leads to designed moments of choice for players: *game mechanics* (Salen and Zimmerman 2004; Adams and Dormans 2012; Juul 2005). Game mechanics are defined by the designer and are decision points at which players trade-off various possible outcomes. In digital games, these choices may be very fast, occurring in the order of milliseconds. The *core mechanics* are the choices that players make repeatedly, forming the essence of a game (Adams and Dormans 2012). The present research develops a set of game mechanics for simulating drone interactions with wearable computers in a mixed reality.

Prior Disaster Response Simulations

Prior disaster response training simulations address a wide range of skills including team coordination (Toups and Kerne 2007; Toups, Kerne, and Hamilton 2011), decision making (Silva et al. 2012), and planning (Toups, Hamilton, et al. 2016; Alharthi, Torres, Khalaf, Toups, et al. 2018; Alharthi, Torres, Khalaf, and Toups 2017). Supporting team coordination and decision-making training through the use of a scenario-based mixed reality simulation has been used, allowing responders to coordinate with each other in real-time, face-to-face and remotely, to mitigate a simulated disaster (Fischer, Jiang, et al. 2014; Alharthi, Sharma, et al. 2018). These types of live mixed reality simulations also provide training opportunities for human-agent coordination and collaboration (Ramchurn et al. 2016; Fischer, Greenhalgh, et al. 2017), helping responders to build advance coordination skills. Advances in personal computers and wearable technologies have the potential to enhance the design of mixed reality experiences and training (Feese et al. 2013). All of these prior studies provide innovative approaches to the design of disaster response simulation, pushing forward the adoption of advanced technologies to support training.

ARCHITECTURE FOR SIMULATING DRONES IN MIXED REALITY

We have developed an architecture designed to incorporate drone simulation with multiple physical-world wearable devices and planners; Figure 2 provides a diagram explaining the architecture. Its primary components include a *request handler*, which manages goals and drone state in communication with the planner. The *planner* is responsible for identifying which drones will respond to a request and how. Once a plan is formed, the *action processor* manages communication either directly with the drone controller or with specialized components that are purpose-built for particular actions. The *drone controller* then interfaces with the virtual world to simulate drones. In the remainder of this section, we provide more detail on the architecture, beginning by explaining the Robot Operating System (ROS)[4].

The simulation is realized using Gazebo Simulator 7.0 with a drone model developed by Meyer et al. (2012)[5]. We use the ROS Kinetic Kame to manage a number of components, including Gazebo. Components running under ROS are called *packages*, and each package may contain multiple *nodes*. A node is a process that performs computation. ROS manages nodes and provides communication between them.

Figure 2 shows a high-level view of our architecture where blocks are nodes. Apart from normal blocks, there are two other types of blocks: stacked blocks and blocks with dashed-lined border. Stacked blocks represent multiple node instances running in parallel (e.g., request handler has multiple instances to support potential multiple incoming goals from multiple wearable devices). Blocks that directly manipulate the virtual world are emphasized using dash-lined border. The simulated drone model works in conjunction with virtual world in Gazebo simulator.

The system is designed to have wearable devices swapped in and out for particular scenarios (e.g., one might involve a touch screen, another might involve a gesture device). The state publisher will remember the set of connected devices and provide, in real-time, necessary status information for the connected devices to know what is going on in the virtual world. When a device wants to make change in the virtual world, it will send its *goal* to the request handler. Depending on the goal, the request handler may combine the current drone state with the goal and request a plan from one of the planners through planner handler. Eventually, a plan (i.e., sequence of actions) will be sent to action processor.

The action processor knows the current drone state from drone controller, and, depending on the plan from request handler, it may make use of specialized component(s). The action processor is implemented using Actionlib[6], which provides a standardized interface for systematic management of the execution of actions, enabling monitoring and/or cancelling ongoing actions.

[4] `http://www.ros.org`
[5] `hector_quadrotor`: `http://wiki.ros.org/hector_quadrotor`
[6] `http://wiki.ros.org/actionlib`

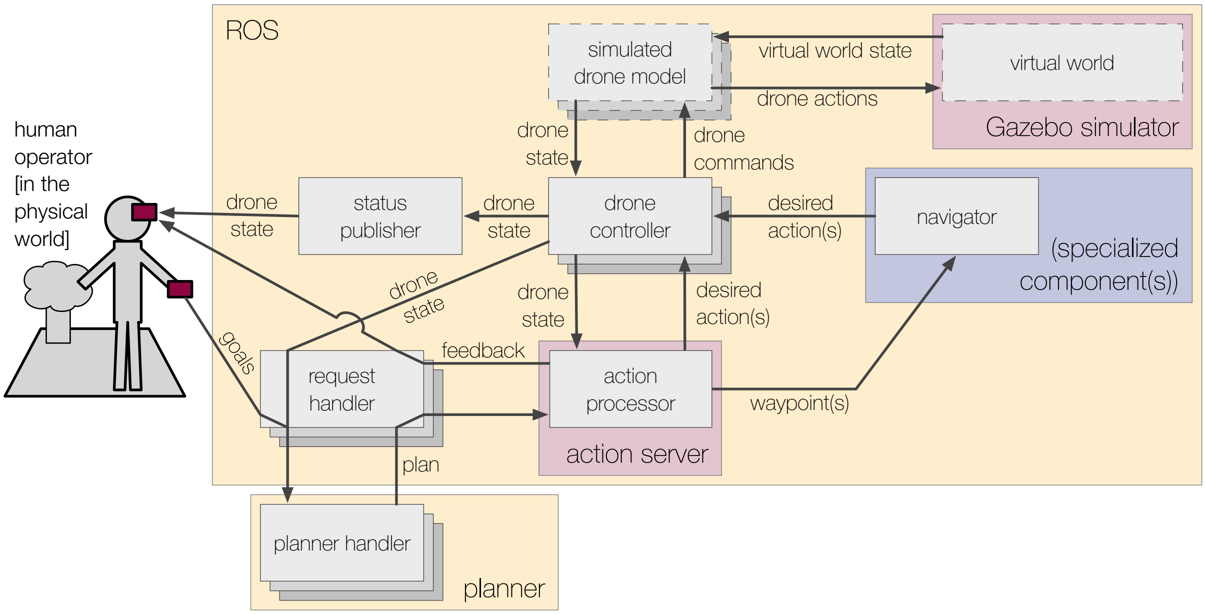

Figure 2. Overview of architecture for mixed reality simulation of drones. The ROS component contains a number of nodes (internal blocks). Stacked blocks represent multiple instances, each with its own state. Blocks with dashed lines border represent virtual entities. To walk through starting from the human operator: the operator enters goals, the planner develops a plan (series of actions), which is then fed to the action processor by the request handler. The action processor uses data about drone state to either push desired actions to the drone controller or send it to one or more specialized components (the present system has a navigator for managing moving drones). The drone controller sends commands to the simulated drone model, which uses the virtual world to enact the specified actions. Finally, information feedback to the user via the request handler. The status publisher provides real-time update of drones' status to the connected wearable devices.

Regardless of what components action processor may use, the desired actions will eventually be sent to drone controller. The drone controller takes care of directly controlling the virtual drones (e.g., flying, hovering). It works at a level higher than simulated drone model, which takes care of actual physics of the drones. The action processor will interpret results from the drone controller, and provide feedback through the request handler of that request if necessary.

While the architecture has been designed for simulating drones in mixed reality, the architecture is general enough to be adjusted to use on other kinds of unmanned systems. System designers would need to change our simulated drone model, drone controller, and navigator (or any specialized components) with their components to suit their projects.

A MIXED REALITY GAME WITH SIMULATED DRONES

We are developing a game that builds on the designed architecture and serves to create a stressful environment (Toups, Kerne, and Hamilton 2011) that requires players to pay attention to simulated drones while maintaining situation awareness (Endsley 1995; Wuertz et al. 2018) of the physical world. The game serves as a starting point to address the issues of team configurations, search and rescue methods, and device configurations. We do not expect this single game to serve to answer all questions, but it is a starting point from which other game and simulation designs can be developed and shows how the architecture is valuable.

The game design is an analog of search and rescue in a built environment. It makes use of existing buildings in the physical world and could be played in any environment where players could freely move and be tracked via GPS. Once implemented, we expect to use environments designed to simulate actual search and rescue. For example, Disaster City in College Station, Texas[7] would fit the purpose well.

Device Configuration

The game is played using a single wearable computer, which provides:

[7]`https://teex.org/Pages/about-us/disaster-city.aspx`

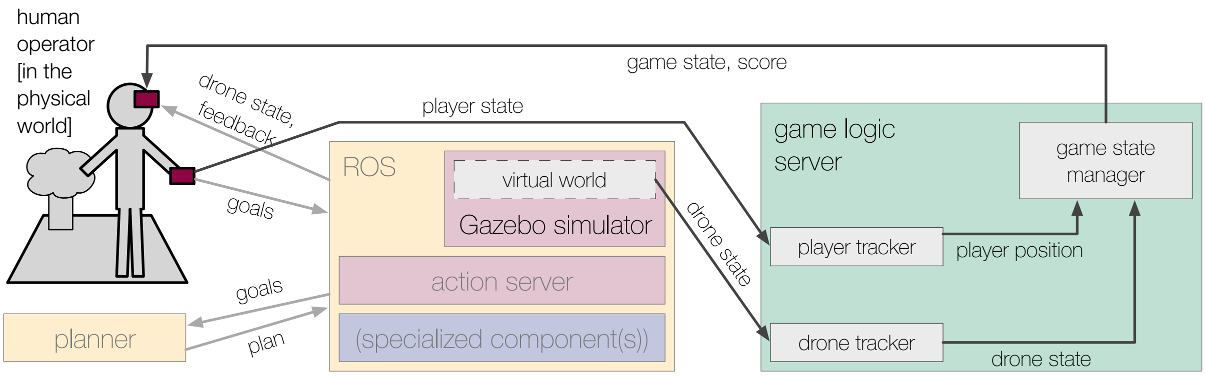

Figure 3. Overview of how the game logic connects to the architecture. Figure 2 is condensed in this figure to show game logic data flows.

- player input: one or more devices for the player to interact with the game;
- player feedback: one or more devices to inform the player of the game state;
- virtual reality simulation: tracking the state of drones via the architecture; and
- game logic: tracking the state of game entities and keeping score.

As part of addressing the issue of device configuration, the wearable can provide player input and player feedback through different composites of wearable devices. The following are device configurations we expect to evaluate, but are only a sample:

- a single touchscreen could serve to show a map: the player sets waypoints via touch and can observe drone status (Figure 4);
- a combination of a head-mounted display could show drone state and a handheld pointer could be used to direct drones in the physical environment; or
- a large, wrist-worn display could show game state while the player uses free-air gestures to provide instruction.

In our design, which presently addresses a single human player and one or more drones, a single wearable computer can serve to run the entire experience. This partially addresses the issue of team configurations (e.g., evaluating when one human works with multiple drones). To address multiple humans in a team, the game could be expanded and run on a wireless network of devices, distributed among players, likely with a single server to provide the virtual reality simulation and game logic.

Objective

The objective of the game is to find a hidden virtual object within one of the multiple structures of a physical built environment. Each structure exists physically, in whatever space the game is set, and has a virtual representation with a four-digit address. The physical structures may contain one of the following virtual elements: a clue, the hidden object, or nothing at all. The player needs to search each structure, either physically or with a drone to find out what it contains. Clues are a part of the address for the structure with the hidden object; clues may be hidden inside a structure (accessible only to the player) or may be hidden on top (accessible only to the drones). Once four unique clues are assembled, the player can use that information to identify the correct structure.

This design element begins to address search and rescue methods, with the player needing to consider trade-offs between performing activities themselves or having a drone perform the activity. The hidden object functions as an analog of in-danger persons or victims, and future games may incorporate more specific features around this concept (e.g., need for medical / psychological support, moving victims).

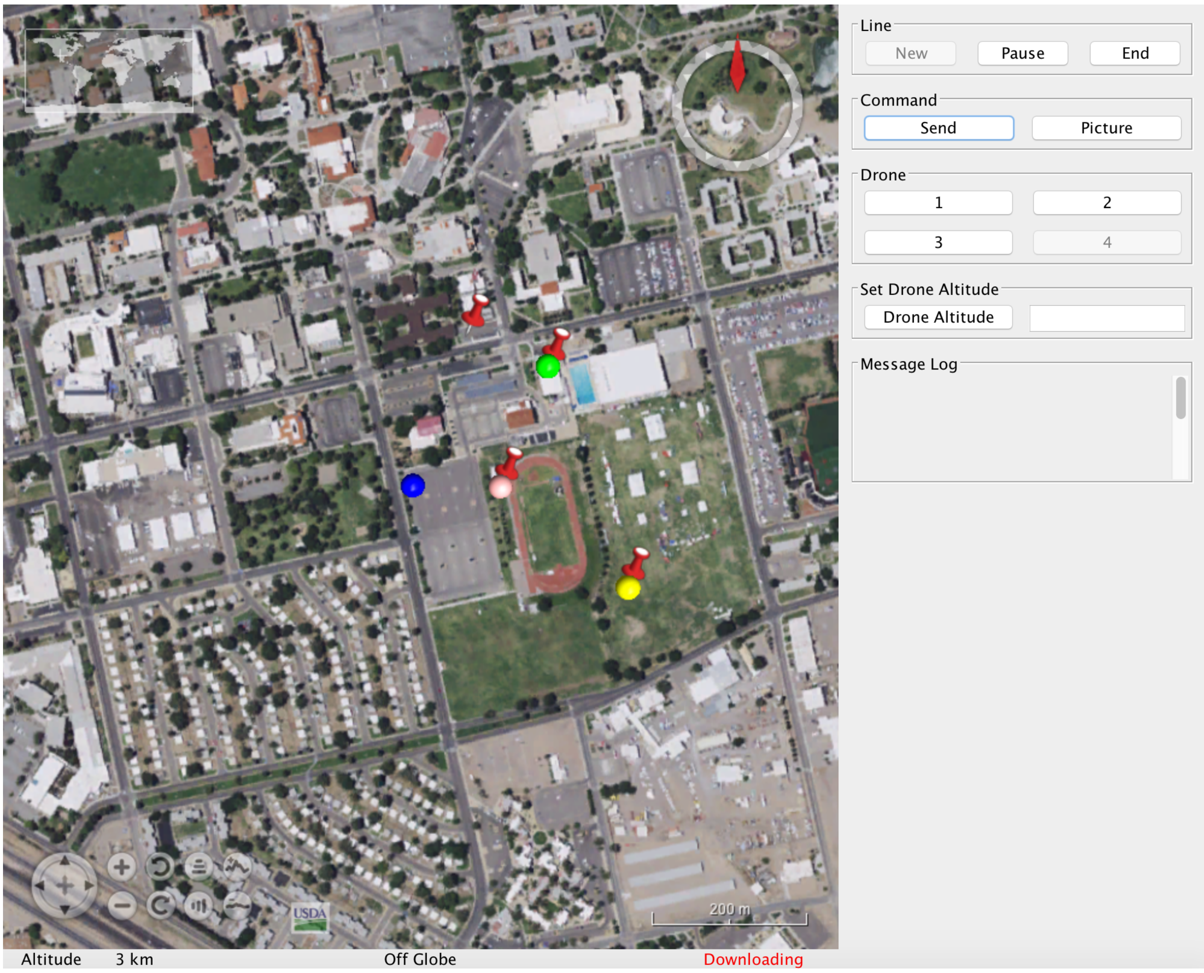

Figure 4. The map interface can be displayed on a wearable device to allow the user to set waypoints and check drone status.

Rules

There are two main constraints that limit player actions: time and drone battery. The game ends if time runs out, limiting the number of structures the player can visit. If a drone's battery runs out, it can no longer be used.

Because pausing to direct the drones will slow down the player, they are encouraged to attend to the wearable computer while moving in the physical environment. The drones also have a limited battery power, meaning that it is not possible to do everything via drone. This also drives a need to optimally spread out drones in the environment.

Because the game is mixed reality and the player is physically engaged in the game, there is no way to model player health or to balance for physical exhaustion. Consequently, the time and battery constraints are used to simulate some of these elements. Certain parts of terrain are dangerous either to the player or to the drones, and can detected remotely by the drones. If a player spends time in a dangerous area, time is deducted; likewise, if a drone spends time in a dangerous area, the drone loses battery faster.

Core Mechanics

To achieve the objective, the player may engage in core mechanics of moving in the physical environment or performing one of several drone actions, while avoiding dangerous areas. A key component of success, and a focus in developing game balance, is attention to how the player optimizes their own movement and the movement of the drones.

Player Mechanics

The player is free to move in the physical environment, to the limits of a specified play area. Because the game is timed, the player needs to focus on moving to the right structures with the help of intelligence provided by drones.

Figure 5. The physical prototype, a paper board game simulating the mixed reality game. A.: the human board with a bar for tracking amount of movement; B.: low-altitude drone board with detailed information; and C: high-altitude drone board with less detailed information.

At the same time, the player needs to identify and avoid virtual dangerous areas while navigating the physical environment to structures that contain clues or the hidden object. The player can search a structure if it is nearby, but this takes time. Ideally, the player should only search buildings that contain clues inside it or the hidden object, as determined by invoking drone actions.

Drone Mechanics

The player can fly the drone on top of the area to scan the map to find the location of the structures, their numbers, their entrance doors, and the most efficient route to get to each building door. Moreover, the drone can check if there is any clue on the top of a structure. The drone user interface is expressly not yet defined, as developing the interface and configuring devices is part of the research.

Similar to the player, there are dangerous areas to drones that deplete their batteries faster. This simulates, for example, needing to maneuver around trees.

The player can make choices about drone altitude. Different altitudes offer trade offs: they may avoid dangerous areas and provide a wider scope of information, but can scan in less detail.

Early Design Stage

We built a physical low-fidelity prototype for our game to evaluate and improve the game and its core mechanics (Rogers et al. 2011; Fullerton 2014). Such a prototypes are built inexpensively, to enable rapid redesign. In our case, as with many digital games, we prototype as a board game that will provide clear insights into how to build the mixed reality. As is the norm for this type of design work, we developed a number of prototypes and played them in the lab to develop the mixed reality game design described previously. In the remainder of this section, we describe the second major prototype we developed.

Our physical prototype is built on three boards, which represent the human's environment, the drone's low-altitude board, and the drone's high-altitude board (Figure 5: A, B, and C, respectively). All boards are the same size, a 6×6 grid that represent the same physical-world space. The boards each contain different sets of information, hidden by paper flaps:

- the human board consists of open space and building locations;
- the low-altitude drone board contains more detail (e.g., buildings, clues, dangerous for the drone and the player); and
- the high-altitude drone board contains low-detail information (e.g, building clues, dangerous areas for the drone only).

One token represents the human and one or more different-colored tokens represent drones.

At the beginning of the game, the human board and drone boards are completely covered. On each turn, the player can specify what the human does: either give a drone a destination or move themselves. If a drone has a destination, it moves as specified. Then, the information on the board is revealed at each location (e.g., that of the human and each drone).

Because the physical prototype needs to be turn-based to enable humans to manage it, the time and battery constraints are modeled by using the number of squares moved. Each of the human and drones has its own pool of movement points. Normally, moving one square costs one point, but dangerous areas (represented as black squares) cost four. Similarly, it costs a drone one point to move a square, two points to increase altitude, one point to decrease altitude, and two points to move through a dangerous area (red squares). The player can direct a drone by spending one movement point.

Revealing information on the board works as explained in the mixed reality game section. The game is won if the player reaches the specified building before their human movement pool is expended.

DISCUSSION

In this section, we address the trade-offs involved in using the architecture to address future search and rescue scenarios. We also discuss our plans for future work in this space.

Benefits of the Architecture

The present architecture enables the safe use of drones in a number of contexts, as well as enables developing replayable scenarios. Drones are challenging to work with and can be dangerous. Many studies have addressed the problem of using drones, such as privacy violation and security issues (Lidynia et al. 2017; Chang et al. 2017). Also, there are legal limits on where and how they may be flown (Barin et al. 2017), which can be at odds with work that needs to consider how they might be used autonomously. Using simulated drones sidesteps many of these issues, enabling a player to have a near-seamless experience of working with drones while also working in a physical environment.

One of the main benefits of using mixed reality through this architecture is the ability to present a contextual experience that use the physical world as a stand for the game world (Benford and Giannachi 2011). Unlike the complete artificial world of virtual reality, mixed reality combines virtual reality information with a physical reality experience. Through this approach, we do not need to simulate the environment, we simply use it. The physical environment affords and constrains action in the game through a combination of layout, size, climate, history and purpose (Sharma et al. 2017).

When training scenarios are re-used, participants are able to carry over knowledge from one scenario to another, which can be at odds with learning. The inclusion of virtual components to the simulation, that do not exist in the physical world, supports replayability. These components can be easily reconfigured, or even constructed procedurally (Togelius et al. 2011), creating different experiences with the same physical environment.

Limitations

One obvious limitation is that human players cannot directly interact with the virtual drones. While we expect many use cases to involve drones working in a space away from humans, this could reduce players' sense of immersion when the drones are working nearby.

An alternative design would create more immersion through the use of 3D imagery in an augmented reality environment. In such a setup, players would be able to see the drones projected on their views of the physical world. At the same time, we have concerns about such an approach, since part of the purpose of this work is to enable testing device configurations and an augmented reality setup necessarily requires augmented reality glasses as a device.

Future Work

In future, we will test the fully implemented game with users, primarily to address device configurations. In these controlled user studies, we will assemble a wearable computer into several possible configurations (e.g., those discussed previously) and have users play through the game. We will use the setup to gather performance data automatically, in which the gathered data will be used to evaluate the performance of the players and the different device configurations (Dolgov et al. 2017).

Another straightforward extension of the framework is to work with non-aerial unmanned systems, though the transition is non-trivial. Such unmanned systems require different navigation capabilities and are more challenging to simulate. We would expect to extend the specialized components (Figure 2) to account for these changes.

CONCLUSION

In this paper, we presented an architecture to test new combinations of human and robot teams in the context of urban search and rescue. While we present our own, initial game design, we expect the architecture to be useful to a range of researchers an practitioners, forming the basis for investigating and training within this unique, new domain. Our game design is just one of many possibilities built on this architecture, and we look forward to a variety of games in this space.

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