Special Issue: Dynamic Large-Scale Swarm Systems in Urban Environments: Results from the DARPA OFFSET Program

Regular Article

Adaptable Mixed-Reality Sensorimotor Interface for Human-Swarm Teaming: Person with Limb Loss Case Study and Field Experiments

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Abstract: This paper presents the design, evaluation, and field experiment of the innovative Adaptable Human-Swarm Teaming (α-SWAT) interface developed to support military field operations. Human-swarm teaming requires collaboration between a team of humans and a team of robotic agents for strategic decision-making and task performance. α-SWAT allows multiple human team members with different roles, physical capabilities, or preferences to interact with the swarm via a configurable, multimodal user interface (UI). The system has an embedded task allocation algorithm for the rapid assignment of tasks created by the mission planner to the swarm. The multimodal UI supports swarm visualization via a mixed reality display or a conventional 2D display, human gesture inputs via a camera or an electromyography device, tactile feedback via a vibration motor or implanted peripheral nerve interface, and audio feedback. In particular, the UI system interfacing with the implanted electrodes through a neural interface enables gesture detection and tactile feedback for individuals with upper limb amputation to participate in human-swarm teaming. The multimodality of α-SWAT's UI adapts to the needs of three different roles of the human team members: Swarm Planner, Swarm Tactician Rear, and Swarm Tactician Forward. A case study evaluated the functionality and usability of α-SWAT to enable a participant with limb loss and an implanted neural interface to assign three tasks to a simulated swarm of 150 robotic agents. α-SWAT was also used to visualize live telemetry from 40 veridical robotic agents for multiple simultaneous human participants at a field experiment.

Keywords: muti-user interface, human-swarm teaming, multimodal user interface, swarm simulation

Received: 31 March 2022; revised: 18 September 2022; accepted: 28 December 2022; published: 15 February 2023.

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DOI: https://doi.org/10.55417/fr.2023007

1. Introduction

α-SWAT is an adaptive and configurable human-swarm teaming (HST) user interface (UI) developed to facilitate HST as part of the Defense Advanced Research Project Agency (DARPA) OFFensive Swarm-Enabled Tactics (OFFSET) program under its Sprint 3 effort. Per the taxonomy of Yanco and Drury (Yanco and Drury, 2004), the level of shared interaction in the current HST work focuses on the collaboration between a team of humans (possibly with distinctive roles) and a team of heterogeneous aerial and ground robotic agents to perform tasks relevant to military and rescue field operations. Early examples of HST UIs include the coordination of multiple teleoperated robots for urban search and rescue (Casper and Murphy, 2003; Murphy, 2004; Murphy et al., 2008; Murphy, 2017), as well as the development and use of synthetic task environments to assess team effectiveness for commanding multiple uninhabited air vehicles (UAVs) (Cooke et al., 2007; Cooke and Shope, 2017). HST UIs were also designed for a single person interacting with a team of robots (Bashyal and Venayagamoorthy, 2008; Kolling et al., 2013; Brown et al., 2016). Some previous studies focused on multi-person teams interacting with a swarm system (Chen and Barnes, 2014) using conventional computer monitors (Chandarana et al., 2021; Chen and Barnes, 2021), tablet-based augmented reality (AR) (Patel et al., 2019; Patel and Pinciroli, 2020), or virtual reality (VR) (Clark et al., 2021) for visualization. Despite the potential demonstrated through these works, there is a need for multi-human HST UIs where multiple human team members can visualize and interact with the swarm of robotic agents based on different interaction requirements and roles. Furthermore, there is also a need for UIs that are suitable for multitasking (Chen and Barnes, 2014) and outdoor field use (Reardon et al., 2019). Conventional computer displays are not portable, tablet computers and other mobile devices carried by hands limit multitasking, and VR headsets obstruct a person's field of view.

We developed the α-SWAT system (Figure 1) to address several limitations of existing HST interfaces by employing an innovative sensorimotor UI combined with mixed reality (MR) visualization that provides adaptive input/output modalities depending on the human team member's role, preference, and even physical abilities. α-SWAT recognizes gesture-based user inputs (via camera or a skin-surface electromyography (EMG) device or implanted EMG electrodes), provides haptic feedback (via a wearable vibrotactile device or implanted nerve stimulation), and enables multiple human team members to interact with either an MR swarm simulator or veridical swarm robotic agents, simultaneously. Facilitating HST for multiple humans using immersive MR visualization is novel and addresses the need for multi-user HST interfaces that are suitable beyond line-of-sight outdoor field use. Unlike other display modalities, head-mounted MR displays have transparent screens that do not occlude the human's view of their surrounding environment. MR visualization preserves human's ability to see and move about the field during HST. α-SWAT is also novel in

Figure 1. Conceptual illustration of the multimodal visuo-sensorimotor interface for human-swarm interface. Users—Swarm Planner (SP), Swarm Tactician-Rear (STR), and Swarm Tactician-Forward (STF)—communicate and collaborate with the swarm at the levels of individual robot, subset, and the entire swarm via vision- and sensorimotor-based interaction.

its ability to recognize multi-modal hand gesture commands via camera detection or EMG signals from the skin surface or implanted EMG electrodes. Our system is the first HST interface that enables both able-bodied people as well as people with limb loss through an implanted neural interface to interact with the swarm. The inclusion of people with neural interfaces in our design potentially expands the ability of people with disabilities to participate in HST training and missions. Furthermore, gesture input and tactile feedback are suitable for noisy or hazardous environments that limit natural voice interfaces, including urban search and rescue where heavy equipment is present and respirators are required (Casper and Murphy, 2003; Murphy, 2017), as well as being in close proximity to large swarms of propeller-driven aerial robots. Gesture input also has the potential to enable humans to multitask by interacting with the swarm while using their hands to grasp tactical or rescue equipment (Cauchard et al., 2015; Stoica et al., 2014; Stoica et al., 2012). α-SWAT integrates a swarm simulator that is novel in its demonstration of embedded algorithms for consensus-based task allocation. The embedded autonomous task allocation method is also innovative, as it autonomously assigns tasks to robotic agents through localized communication when given a mission created by the human team member, which has the potential to make HST more intuitive and less burdensome for multiple simultaneous human team members.

The rest of this article is organized as follows. Section 2 details the design requirements set by the DARPA OFFSET program, Section 3 describes the system implementation and rationale, and Section 4 describes a live field experiment demonstration and a system evaluation in a case study involving a participant with upper limb amputation who has an implanted neural interface.

2. Project Requirements

DARPA highlighted the need for novel multi-human HST interfaces by calling for their development as part of the OFFSET Sprint 3 program (DARPA, 2018). Two industry teams, referred to as Swarm System Integrators (SSIs), participated in the multi-year OFFSET program, while smaller sprint teams, like us, were selected to tackle specific technical goals for developing component technologies for potential integration with the system-level platforms developed by the SSIs for a 6-month development period. The Sprint 3 goal was to design innovative HST interfaces that enable multiple tactical team members (represented by three human personas) to collaborate with a simulated swarm of up to 200 autonomous robotic agents. These robotic agents could be UAVs or unmanned ground vehicles (UGVs). The types of collaboration involved multiple humans simultaneously visualizing the status of the swarm, assigning tasks to be performed by the swarm (such as searching an area for a target), and interacting with the swarm in real time when the swarm requests a command/input from the human team member(s). The developed system is expected to support the three hypothetical military personas listed below.

- **Swarm Planner (SP)** plans missions at a potentially remote location prior to the swarm deployment. This is analogous to a “supervisor” in Yanco’s taxonomy (Yanco and Drury, 2004).
- **Swarm Tactician - Forward (STF)** observes and potentially participates in a mission alongside the swarm within the mission operation area in real time. This is analogous to a ‘teammate’ in Yanco’s taxonomy (Yanco and Drury, 2004).
- **Swarm Tactician - Rear (STR)** oversees a mission in real-time from a location adjacent to the operation area or at a remote location with a reliable communication channel with the swarm and STF. This is analogous to a “bystander” in Yanco’s taxonomy (Yanco and Drury, 2004).

Since the SSIs were in the early phases of developing their HST interfaces and swarm hardware platforms, sprint teams needed to initially demonstrate their concepts using simulated swarms. At the end of each 6-month sprint project, both SSI and Sprint teams participated in a field experiment (FX) that encouraged the integration of innovations developed by sprint teams into the swarm platforms being developed by the SSIs. In the third field experiment (FX3), the goal for each SSI was to use an HST interface to deploy a swarm of UAVs and UGVs to find "high-value objectives." These objectives were represented by AprilTag fiduciary markers (Olson, 2011) placed throughout the roads and buildings of an urban training site at US Army Camp Shelby Combined Arms Collective Training Facility outside of Hattiesburg, MS (Clark et al., 2021). The specific goal for our team at OFFSET Field Experiment 3 (FX3) was to visualize the swarm for the SP, STR, and SP personas using telemetry received from an SSI during one of their marker-seeking trials. In addition to FX3, our overall project goal was to demonstrate HST via multimodal UI devices for two or more humans playing different roles and interacting with a simulated swarm where role-specific levels of visualization are realized in an MR environment.

3. System Development and Implementation

We developed the innovative α-SWAT HST interface, enabling multiple humans representing the SP, STR, and STF personas to interact simultaneously with a swarm of over 100 robotic agents. The user interface of α-SWAT was designed to adapt to the different needs of three simultaneous users and visualize a simulated or veridical swarm. The system consists of two main components: (1) a swarm simulator with embedded swarm tactics and task allocation algorithms and (2) a multimodal UI supporting selective use of the various UI devices—an MR display for visualization, hand gesture input (via camera-based, implanted EMG, or skin-surface EMG recognition), and tactile feedback (via vibrotactile motors or implanted sensory nerve stimulation). These two components interface with host computing devices that run Robot Operating System (ROS), MATLAB, and Unity.

3.1. System Architecture

The system's overall architecture with its core components is illustrated in Figure 2. Each human team member wears an immersive head-mounted HoloLens MR display (Microsoft Corp, Redmond, WA), which runs a UI application that visualizes telemetry generated by the Unity Simulation application. The Unity Simulation application runs on a computer that acts as a server and maintains the state of the simulated swarm and MR environment based on a 3D map of the veridical environment. Each HoloLens device runs the UI simulation software that acts as a client and visualizes the MR environment, simulated swarm, and interactive UI. Unity's Photon Networking

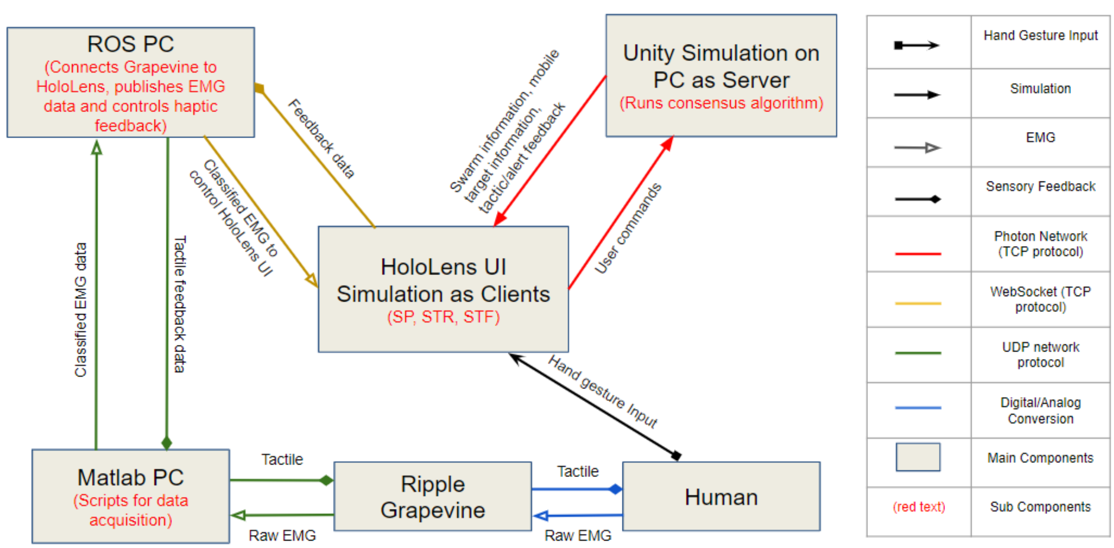

Figure 2. Block diagram of system components. Each arrow type indicates the type of information transferred, while the line colors indicate the network communication protocol that was used.

utility synchronizes swarm movement and tactic data between the server and HoloLens clients over wireless TCP/IP. HoloLens devices also communicate over ROS to acquire user input from the EMG devices and to trigger haptic feedback. A ROS server publishes user hand movement velocities acquired from EMG as ROS topics. HoloLens clients subscribed to these EMG-derived ROS topics using the ROSBridgeLib Unity utility. Additionally, HoloLens clients publish ROS messages to trigger the Grapevine Neural Interface (Ripple Neuro Inc., Salt Lake City, UT) to provide nerve stimulation, which generates tactile feedback to a human with a neural interface.

User inputs are responded to by the following custom Windows MR Toolkit software services running on the HoloLens. The Role Service configures the MR environment to suit the type of persona selected by the user. The Tactic Planning Service is the central controller for adding, updating, deleting, and disseminating tactics to the swarm. The Swarm List Service maintains a data repository that stores the state of simulated swarms. A Repository Service uses Photon Networking to synchronize swarm data repositories between the server and all HoloLens devices.

The swarm simulator was developed in Unity 2018.4.2f1 (Unity Technologies, San Francisco, CA) and ran on a Windows 10 computer (Alienware 15, Dell Inc., Round Rock, TX). Microsoft MR Toolkit version 2.0.0 and Photon networking version 4.0.28.2962 packages were used to implement the HoloLens UI application and synchronize swarm position and task allocation states among multiple HoloLens devices. A Grapevine Neural Interface Processor and MATLAB (Mathworks Inc., Natick, MA) were used for surface and implanted EMG acquisition, as well as haptic feedback via vibrotactile motors or direct nerve tactile stimulation using nerve cuff electrodes. ROS Melodic Morenia (Open Robotics Foundation, Inc., Mountain View, CA), running on an Ubuntu Linux computer, was also used to synchronize the transport of EMG and haptic feedback over TCP/IP.

3.2. Swarm Simulator

The swarm simulator in the α-SWAT system takes human inputs and simulates the swarm's responsive activities, such as visualizing the real-time telemetry, task allocation status, and task execution progress. Within the scope of the presented study, we assume that SP creates a list of tasks where each task description includes the following information: swarm tactic type (e.g., aggregation, dispersion, boundary securing, tracking a moving target), location, workload (i.e., the number of agents required for each task), task duration, and task priority. This list is provided to STR, and STR sends the task list to the simulated swarm. Our simulator has an embedded algorithm for allocating individual tasks to the swarm by forming corresponding task groups. This simulator supports the visualization of real-time telemetry received from veridical robots by mapping the physical locations into the MR environment.

Related work: swarm simulators and swarm task allocation

Several swarm simulators exist, including ARGoS, V-rep, and Gazebo (Pinciroli et al., 2012; Rohmer et al., 2013; Koenig and Howard, 2004), but are not designed for MR interfaces. ARGoS is a multi-physics robot simulator that supports real-time simulation of large heterogeneous swarms of robots (Pinciroli et al., 2012). V-rep offers unique features, such as meshes that can be manipulated in real-time. Other simulators typically do not support real-time manipulation of the meshes (Rohmer et al., 2013; Pitonakova et al., 2018). Gazebo is a general-purpose, open-source robotic simulator offering a seamless interface with ROS (Khaliq et al., 2021). While these simulators have been successfully used for swarm simulations, they are not directly compatible with HoloLens, which is a core UI device for our project. HoloLens requires applications to be developed in Unity and supports easy integration of configurable multimodal UIs. In particular, HoloLens MR visualization is critical for achieving our goal of creating an interface that could visualize simulated and veridical swarm telemetry for different human roles during field experiments and HST activities.

Swarm decision-making aims to either achieve consensus towards a single agreed-upon decision (consensus decision-making) or divide the swarm to perform different tasks (task allocation). Within the scope of the presented work, we assume SP establishes an upper-level mission description consisting of one or multiple tasks to be performed by the swarm, and the swarm assigns the tasks to the robots autonomously or with minimal human intervention. Requiring human team members to manually assign tasks to individual robots for swarms of over 100 robots is time-consuming, impractical, and limits the human's ability to address other responsibilities or tasks. Furthermore, if the swarm operates in a decentralized manner or only has intermittent communication with human team members, the swarm must be able to assign and perform tasks autonomously. If multiple tasks require the entire swarm to collaborate in a sequential manner, task allocation involves determining the priority of the tasks (Brutschy et al., 2014). The majority rule is one of the simplest and most commonly used methods (Wessnitzer and Melhuish, 2003; Kanakia et al., 2016), but it has limited flexibility on initial conditions and external inputs. In contrast, the K-unanimity algorithm allows the speed and accuracy of the consensus process configured via the K parameter (Brutschy et al., 2012; Scheidler et al., 2015). In (Liu and Lee, 2020), each swarm agent is considered a probabilistic finite state machine (PFSM) that selects its decision among a finite number of states via local negotiation with other nearby agents. However, the amount of information exchanged among the agents also increases as the number of options increases.

If the task description includes multiple distinctive tasks simultaneously performed by the swarm, the swarm must be divided into multiple subgroups to perform the tasks (Khaluf et al., 2020; Berman et al., 2009). Time and cost may be subject to optimization in task allocation algorithms. In (Berman et al., 2009), stochastic control policies of individual robots without requiring direct communication were proposed for swarm task allocation. In (Liu and Shell, 2013), a market-based algorithm was proposed to produce optimal assignments by auctioning from a merchant's point of view. In a target-attacking scenario, a two-parent genetic algorithm was developed to assign a task sequence for each UAV in the swarm (Jia, 2019). A modified binary particle swarm optimization was also applied to task allocation for a wireless sensor network (Yang et al., 2013). Faced with constraints, e.g., limiting the total number of agents on a specific task or the total number of visits per location for each agent, a Pareto-based multi-objective model may be used (Di-Ming et al., 2011). Given a complex task, a swarm may decompose it into multiple simpler subtasks (Lee et al., 2020; Brutschy et al., 2014; Pini et al., 2013). Many of these works focus on analyzing the tasks and forming the groups, which would require significant time and cost for processing. In time-sensitive military and search-and-rescue operations, fast and reliable strategies for rapidly assigning a given list of tasks and executing them would be the priority in such applications. Our simulator's embedded task allocation algorithm aims to take a list of tasks with minimal associated descriptions shared among the swarm through the local network. The swarm then forms task groups to execute the tasks via embedded task allocation.

Technical and operational assumptions of the simulation environment

Our swarm simulator was established under the following assumptions. First, we assumed that individual robots have onboard processing, memory, and communication capabilities for simulations. Second, robotic agents in a connected network form a swarm, and there may be one or more swarms operating simultaneously—whose formations may change dynamically. Third, at least one human persona has wireless communication maintained with at least one robot (but not a specific one) in each swarm; otherwise, the disconnected swarm will operate independently in a fully autonomous manner. Fourth, each robotic agent was assumed to have an existing set of pre-programmed swarm algorithms. Swarm algorithms refer to individual actions programmed in each robot that are executable by the robot. Each of these algorithms corresponds to a swarm tactic, which refers to collective swarm behaviors or tasks achieved by a group of robots that individually execute a specific swarm algorithm simultaneously. A collaborative swarm tactic can be achieved when the robots in a connected network run the same algorithm simultaneously.

Customized 3D models were created for UAV and UGV visualization in Unity. For the UAV, a generic quadcopter model similar to the physical UAV platforms used by both OFFSET SSIs was developed (Figure 3-left). Figure 3-right shows the design of the UGV, which was based on the AION-M6 (AION Robotics Inc., Westminster, CO)—one of the physical UGV platforms. Each

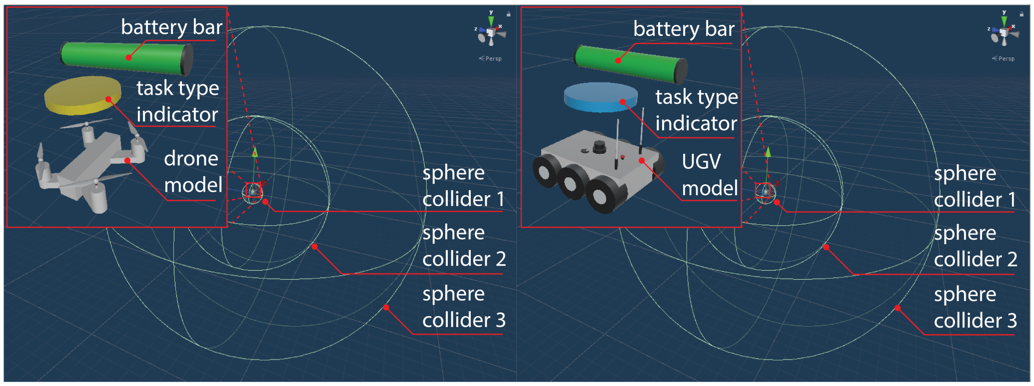

Figure 3. (Left) Aerial robot model and (right) ground robot model with visual information indicators and three sphere colliders defined for collision avoidance, local consensus communication range, and information diffusion range in Unity. A disk above each robot represents the agent's task type (e.g., yellow - "surveillance"; blue - "target tracking").

of these models contains the following components: the first collider for determining the collision avoidance range (Collider 1); the second collider for determining the robot-to-robot communication range for task allocation (Collider 2); the third collider for determining the robot-to-robot information flow range (Collider 3); 3D robot model with textures; unique robot ID assigned for each; tactic indicator (circular disk displayed over each robot) visualizing the specific task assigned to the robot; and a battery bar indicating the remaining battery capacity. These visualizations are 3D adaptations of glyph concepts for remotely piloted aircraft systems described in (Calhoun et al., 2016) and based on data transmitted by robotic agents used by the Raytheon BBN (Cambridge, MA) Command and Control of Aggregate Swarm Tactics (CCAST) team (Clark et al., 2021) and our distributed task allocation algorithm embedded in the simulator. Both ground and aerial robotic agents in our simulator were programmed with the following capabilities.

- **Locomotion.** Aerial agents can move in 3D space, and ground robots can move over a surface.
- **Collision avoidance.** Each UAV/UGV has an embedded collision avoidance algorithm that commands the robot to either wait or detour when encountered by another agent within the boundary defined by Collider 1. When the angle between the moving directions of the two agents is smaller than 90°, the UAV/UGV waits until the encountered agent is out of Collider 1's range. Otherwise, it detours by processing a displacement perpendicular to its current path and proceeds with its goal.
- **Localized peer-to-peer communication.** By modulating Collider 2 and 3, the local communication ranges for task allocation and information flow can be adjusted, and the number of robots within the range can be identified. During the consensus process, the exhibited decisions are updated and shared through the entire swarm through information flow. Individual agents terminate the consensus process when the number of task group members reaches the corresponding workload.
- **Task allocation algorithm.** A consensus-based task allocation algorithm is embedded in individual robots, and any robot can trigger consensus for task group formation or joining a task group. Collider 2 determines the communication range for this algorithm.
- **Swarm algorithms.** Each robot has a set of embedded swarm algorithms, each corresponding to a swarm tactic, which we conceived to be relevant based on prior OFFSET field experiments. Embedded swarm algorithms include (i) *boundary securing*, for which robots will first aggregate at the target and then spread out to secure the area by forming a circle (**Algorithm 1**); (ii) *aggregation*, for which robots gather closely around the target location; (iii) *dispersion*, for which robots first aggregate at the target localization and then spread out while keeping a certain

Algorithm 1. Boundary Securing (Tactic 1).

Result: A group of robots evenly distribute and form a loop around the target location.
Secure boundary tactic initialization (receive target location and confirm team member IDs);
Assemble at the target location;
if *All team members finish assembling* **then**
  | Calculate moving direction based on relative positions of neighbor nodes
end
while *Circle boundary condition is not reached* **do**
  | Move in the calculated direction
end
if *All team members stop on the circle boundary* **then**
  while *At least one team member moved within the last 5 seconds* **do**
    if *there are more neighbors on my left side* **then**
      | move counterclockwise on the boundary (top view)
    else
      | move clockwise on the boundary (top view)
    end
  end
end

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distance from their neighbors; and (iv) *target tracking*, for which a small group of robots will follow a moving target and request a command from the human to either ignore or disable the target.

Based on these features, simulated swarms have the following autonomous capabilities: they can (1) receive an upper-level task plan created by the SP and trigger the task allocation function, (2) make decentralized consensus-based decisions for allocating tasks via localized communication, (3) perform swarm tactics by individual robots executing simple swarm algorithms, (4) reprioritize tasks based on priority conditions predefined by the SP and STR personas, and (5) return to a designated base when the battery level is lower than the pre-defined threshold.

Consensus-based task allocation and swarm algorithms

In this swarm simulator, individual robots are modeled as adaptive probabilistic finite state machines (PFSTs), each with n states representing the number of embedded swarm algorithms. Therefore the swarm can also be viewed as a PFST, where the distinctive swarm behaviors represent the states. The mission description, created by SP, includes a list of abstracted tasks (i.e., index numbers corresponding to embedded swarm algorithms and tactics), workload (defined by the number of robot agents needed for each task), and completion time. This list is disseminated among the swarm, assuming that a subset of the swarm receives the list and shares it with the entire swarm via local communication. The embedded task allocation algorithm allows the swarm to form a task group for each task. The index numbers of the tasks in the task list form a decision space for each robot, and the robots within the local communication range exchange the index with the highest preference and its decisiveness with each other. Decisiveness reflects how certain the robot is towards the most preferred choice and is defined for each robot k as $\Omega_k = (1+H_k)^{-1}$, where $H_k = -\sum_{i=1}^{n} P_i^k \log_2 P_i^k$ for P^k being the probabilistic mass function over n possible choices. Local negotiation continues until the task group size with the same decision reaches the corresponding workload, after which the task is executed.

Swarm algorithms embedded in each robot correspond to expected swarm tactical behaviors required/expected by the swarm. Some common swarm tactical behaviors include foraging (Gazi and Passino, 2004; Lu et al., 2018), aggregation (Gasparri et al., 2012; Leccese et al., 2013), or global shape formation (Rubenstein et al., 2012; Fu et al., 2020). The presented work considered four swarm algorithms targeting the following swarm tactics: boundary securing (Tactic 1), aggregation (Tactic 2), dispersion (Tactic 3), and surveillance (Tactic 4). Each tactic can be achieved by a group

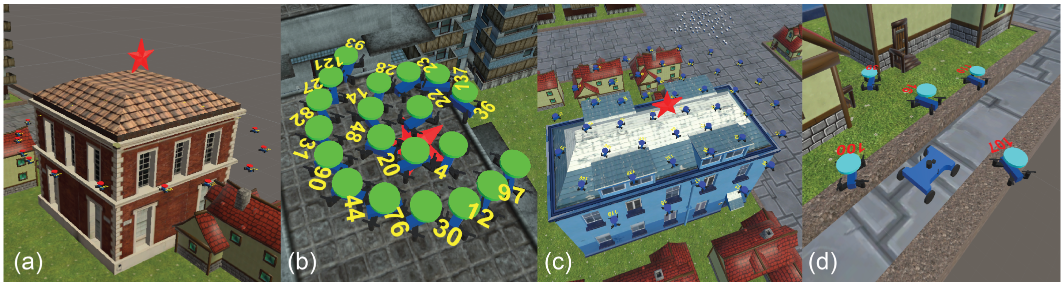

Figure 4. Tactics illustration. (a) Tactic 1: Loop formation. (b) Tactic 2: Aggregation. (c) Tactic 3: Dispersion. (d) Tactic 4: Surveillance.

of robotic agents executing the corresponding swarm algorithm. These algorithms are simple and operate in a distributed and localized manner under the limited robot-to-robot communication range defined by Collider 2. The boundary securing algorithm (Swarm Algorithm 1) enables each robot to find the two nearest robots and keep itself in the middle of the two while maintaining a certain distance from each other. When a group of robots executes the same algorithm, the group forms a loop, corresponding to Tactic 1, as shown in Figure 4-a. **Algorithm 1** shows the pseudo-code for this algorithm. The aggregation tactic (Tactic 2, Figure 4-b) is achieved by forming multiple layers of circular rings around the target point. For this tactic, the agents move towards the target task location and start forming rings starting from the innermost ring. Each agent moves in the CCW direction around the ring until it reaches an available spot while maintaining a pre-defined distance. Once each ring runs out of space, the agents start a new outer layer. The aggregation tactic is accomplished after all agents encircle the target location, with each individual staying on one of the rings. To proceed with the dispersion tactic (Tactic 3, Figure 4-c), the group first executes the aggregation tactic at the target point, and then the robots push each other based on the combined force from the three closest neighbors calculated by the "spring-damper model" (Jeong and Lee, 2014; Wiech et al., 2018) until this force is smaller than a certain threshold. Lastly, the surveillance tactic (Tactic 4, Figure 4-d) requires a certain number of robots tracking and following a moving target. Whenever a moving target appears within a detectable range, the agent(s) triggers consensus to recruit other agents for this task. Based on the IDs of the agents, each is given a specific relative position with respect to the moving target. The agents keep tracking and following the target until the inspection is completed. The number of embedded swarm algorithms forms a decision space where the task description would include a list of tasks to be completed by the swarm agents by executing the swarm algorithms.

3.3. Multi-human, Multimodal User Interface

The UI of α-SWAT consists of configurable UI devices with associated software to support multi-human, multimodal interaction between the human team members and the robotic swarm. The multimodal UI enables visual-, tactile- and audio-based interaction. Its specific modality can be different depending on the user's preference, availability of the UI devices, and physical status. The types of interaction realized by this UI consist of swarm visualization, gesture detection, as well as audio and haptic feedback.

Related work: MR, EMG, and gesture-based swarm user interfaces

A large body of work exists for swarm interfaces (Suzuki et al., 2022), including joysticks (Murphy, 2004), multi-touch display interfaces (Kato et al., 2009), stylus-based haptic devices (Setter et al., 2015), gesture-based interfaces (Cauchard et al., 2015), gaze-based interfaces(Erat et al., 2018), and physiological interfaces that use signals such as skin-surface EMG (Stoica et al., 2012) and EEG (Karavas et al., 2017). Tangible swarm UIs have also been demonstrated to enable a human planner to manipulate miniature robotic agents or figurines on a tabletop to interact with veridical objects or computer-generated images and maps projected onto the table surface (Le Goc et al., 2016; Ducasse et al., 2018; Kim et al., 2020).

There is emerging evidence that immersive head-mounted displays benefit HST. Head-mounted VR displays for drone teleoperation improved situational awareness and spatial understanding compared to conventional monitors and large projection displays (Ruiz et al., 2015). However, head-mounted VR displays occlude the human team member's view of the veridical environment, making it not applicable for real-time field operations. On the other hand, MR displays use a transparent screen that enables human team members to see their surroundings and interact with other people and robots. Also, computer images can be projected onto veridical walls to achieve "x-ray vision" of the contents behind it, which has been shown to improve the teleoperation performance of a single drone versus using a first-person view from a camera onboard the drone (Erat et al., 2018). HoloLens was recently demonstrated to be viable for military field experiments when used as a single-robot MR user interface (Reardon et al., 2019). MR interfaces that allow humans to interact with the environment in addition to the swarm have also reported increased efficiency for assigning tasks to swarms (Patel et al., 2019; Arthur et al., 2020). It is unknown if MR UI designs scale well to multiple simultaneous humans or a large swarm that can conduct multiple tasks in parallel, but such capabilities are highly relevant for military or rescue operations and warrant investigation. α-SWAT adopts an MR-based swarm visualization, which allows simultaneous, multi-level interaction between multiple humans and the swarm.

Gesture-based interfaces can also benefit HST and be intuitive for human input. Previous research showed that operators used only hand gestures to command drones twice as frequently as voice commands or voice combined with hand gestures (Cauchard et al., 2015). Others reported that hand gesture drone inputs were easier to use and more effective than conventional keyboard input (Rogers, 2018). Hand gestures are typically detected using optical tracking, but they can also be detected using EMG. EMG drone interfaces have been developed for situations when the hands are not free to perform gestures, such as when humans need to hold equipment during multitasking to issue swarm commands (Stoica et al., 2012; Stoica et al., 2014). Skin-surface EMG has been used to detect 17 hand gestures for swarm control (Stoica et al., 2014), as well as replicate conventional joystick-based remote controls or control individual drones in combination with inertial sensors (Altın and Er, 2017). Wearable EMG devices have also been used to show that multiple operators using them can complete HST tasks faster than a single operator (Nagavalli et al., 2017). Compared to skin-surface electrodes, implanted nerve interfaces may be more suitable for daily use, but they have not been utilized for HST interfaces previously. Implanted electrodes that do not require donning and doffing can acquire higher quality EMG and can provide spatially and modally congruent tactile as well as proprioceptive haptic feedback through electrical stimulations.

There is emerging evidence that haptic feedback benefits human-swarm interaction (Nunnally et al., 2019). Haptic feedback has been shown to help swarm operators find more targets and cover more area (Nunnally et al., 2013). However, providing haptic feedback to the human member requires additional physical devices, which may not be portable or suitable for outdoor use. Wearable haptic teleoperation systems that work well in a fixed location include soft exoskeletons driven by cables (Rognon et al., 2018) or pneumatic bladders (Rognon et al., 2019), which have been shown to reduce flight trajectory error and human workload for simulated quadcopter operation. More portable glove-based systems have used inertial sensors for trajectory control in combination with vibrotactile motors to provide haptic feedback (Ibrahimov et al., 2019; Tsykunov et al., 2019). Our team's prior work demonstrated that a person with an upper extremity amputation and percutaneous implanted direct nerve interface could control a virtual hand using EMG and perceive tactile and proprioceptive sensations provided by electrical stimulation (Dewald et al., 2019; Schiefer et al., 2018; Schiefer et al., 2015). To the best of our knowledge, our system is the first interface designed to extend the abilities of people with limb loss to HST. The literature on human-robot interfaces for people with disabilities has primarily focused on prosthetics (Rosen, 2019), motor training assistance (reaching/grasping, walking) (Rosen, 2019; Artemiadis, 2014), social assistance during training (Feil-Seifer and Matarić, 2011), and execution of activities of daily living (dining, mobility)(Brose et al., 2010). HST interfaces that are inclusive of people with neural interfaces have the potential to create new professional reintegration opportunities for people with limb loss.

UI design overview

In α-SWAT, each persona's UI was designed to align with their mission roles, as described in Section 2. Swarm visualization can be realized by either a conventional computer monitor or head-worn displays, such as HoloLens. A conventional 2D display may suit the SP persona, who plans the overall mission, but it is not ideal for STR or STF, who interacts with the swarm in real-time. The current work focuses on MR-based swarm visualization using HoloLens, which is adaptable for all three personas. A camera mounted in the MR device or a surface/implanted EMG device is used for human gesture detection. A neural interface or vibrotactile motor is used for human haptic feedback. The system also allows the human user to change the UI mode as required by their role. For example, a person initially assigned as STR may become STF performing tasks at the veridical operation site. This section presents detailed visual UI designs for the three distinctive operation modes: SP, STR, and STF. Each HoloLens, used as the MR device, initializes to one of the three SP, STR, or STF modes based on the persona selected by the user. In all persona modes, users interact with virtual objects in a veridical environment by pointing at them with a "gaze cursor" and making a hand gesture, referred to from here on as a "selection input." The rationale for this design was to utilize a familiar, intuitive interaction modality analogous to a computer mouse. The gaze cursor is native to HoloLens and appears as a small dot that always stays at the center of the user's field of view, projecting forward onto any virtual or veridical surfaces. The HoloLens Air Tap hand gesture can trigger the user's selection input, which is natively recognized by HoloLens' onboard cameras when the index finger and thumb make contact. Auditory feedback is also provided to confirm that selection inputs were recognized or disseminated to the swarm.

MR-based visual interaction with the swarm

The environment and swarm are visualized at two different scales and perspectives: (1) a bird's eye view of a miniaturized 3D map and the swarm with status icons (Figure 5-a) and (2) a 1:1 scale view of a virtual swarm overlaid upon a veridical environment and viewed through the first-person perspective (Figure 5-b). Both maps show the same area, but the miniaturized map was made to appear in front of the user on a 2×2 m table surface to facilitate mission planning. In contrast, the 1:1 scale map was made to appear semitransparent (by setting the 3D texture alpha channel = 0.33) and aligned with the environment so that users would have x-ray-like vision ability to see the swarm beyond their line of sight. Real-world map data was sourced from OpenStreetMap.org and edited using JavaOpenStreetMap Editor, OSM2World, and Blender software applications before being imported into Unity. Although OpenStreetMap data did not include building heights, we referenced construction blueprints and adjusted them to visually match the veridical buildings as seen through the 1:1 scale first-person perspective.

The 1:1 map was calibrated to the veridical environment using the following procedure. We first set each persona's perspective to start from a predefined initial position and orientation in the virtual environment corresponding to a veridical location and orientation from where each HoloLens client application is initialized. Then, we visually placed two virtual Unity "world anchors" so they coincided with veridical markers placed at 0.5 m on the ground in front of and behind each human's initial position. This aligns the 3D map models so that they appear colocated with the veridical environment, landmarks, and buildings as shown in Figure 5-b.

Three human team member roles: SP, STR, and STF

We assumed that SP plans a mission from a remote location before the swarm is deployed. For this role, the user is presented with a 3D map of the operation area that is scaled-down and positioned near waist-level to appear like a table-top model (Figure 5-a). A mission is planned by creating swarm tactics on a tactic configuration window positioned above the map and to the right of

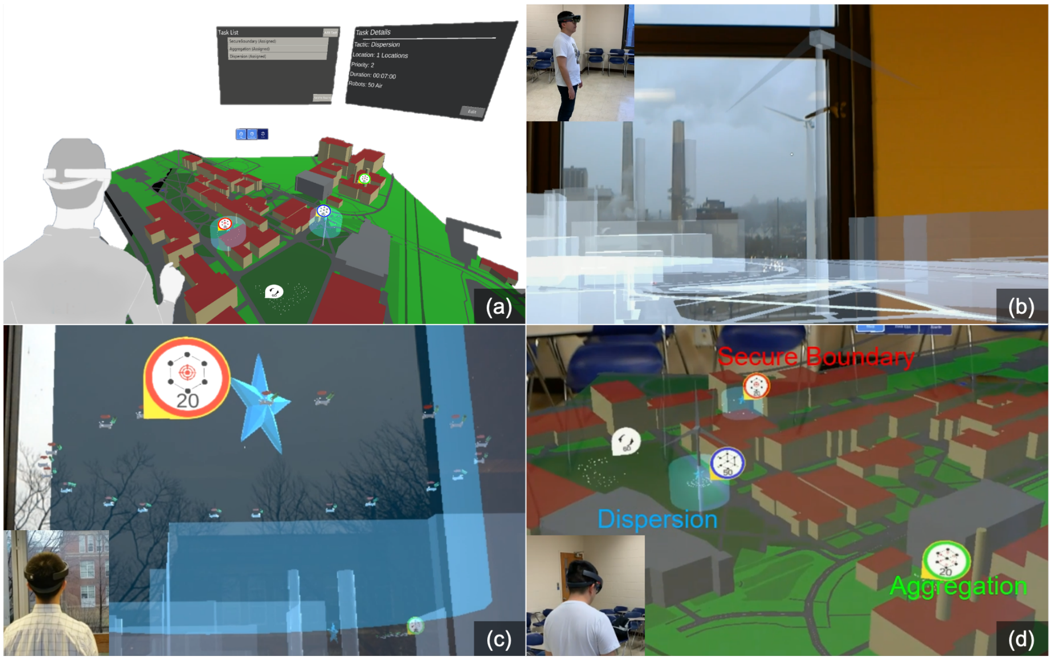

Figure 5. (a) A miniaturized map with tactic planning interface windows floating above the map for SP and STR visualization and (b) a transparent 1:1 map overlaid upon the veridical environment from the first-person view for STF and STR visualization. Both lower panes show a simulated swarm experiment at the same point in time from two perspectives: (c) STF's ground-level view through HoloLens using the 1:1 first-person map view and (d) STR's view through HoloLens from inside a nearby building using the miniaturized map with circular icons that show the tactic each group is executing.

the tactic list. The configuration window sequences were designed to align with FAA guidelines for multi-function displays that minimize mode confusion (Chamberlain et al., 2013). Specifically, this window is placed above the map and beside the window of the task list so that it does not obstruct other information (Figure 5-a). Through clearly labeled interactive buttons, an operator can cancel the tactic configuration sequence or proceed to the next action. Auditory and haptic feedback to the SP is also limited to confirmation of button presses, which minimizes the risk of sensory clutter and hearing loss. To add a tactic to the list, users select a tactic to configure from an array of possible choices (Figure 6-a). Next, users mark a target location on the map where the swarm should implement the tactic. This is done by placing the gaze cursor on the map and performing a selection input, which marks the location with a star (Figure 6-b). Tactics that require humans to define a region of interest will present a semitransparent cylinder centered about the star, whose radius scales with the movement of the gaze cursor. The cylinder's radius is preserved by making a second selection input (Figure 6-b). After finalizing the tactic's target location, the tactic configuration window will prompt the user to define the duration that a swarm should maintain a tactic (Figure 6-c). The hours, minutes, and seconds can be incremented or decremented by intervals of 1 or 5 using the buttons below the time display. Subsequently, the desired number of robotic agents that should implement a tactic is defined using a similar interface, shown in Figure 6-d. Once all tactics are defined, the tactic list is transmitted to the Swarm Tactician-Rear's user interface by triggering the button labeled "Send to STR" at the bottom right corner of the task list (Figure 5-a). After the list is successfully transmitted to the swarm, audio and haptic feedback are provided to the human. Furthermore, target locations and regions of interest remain visible to all humans (Figures 5-a, 5-c, and 5-d) along with real-time tactic status icons.

We assumed that STR is positioned near the boundary of the operation area. Their role is to deploy the mission created by SP to the swarm and oversee its implementation. To suit this role,

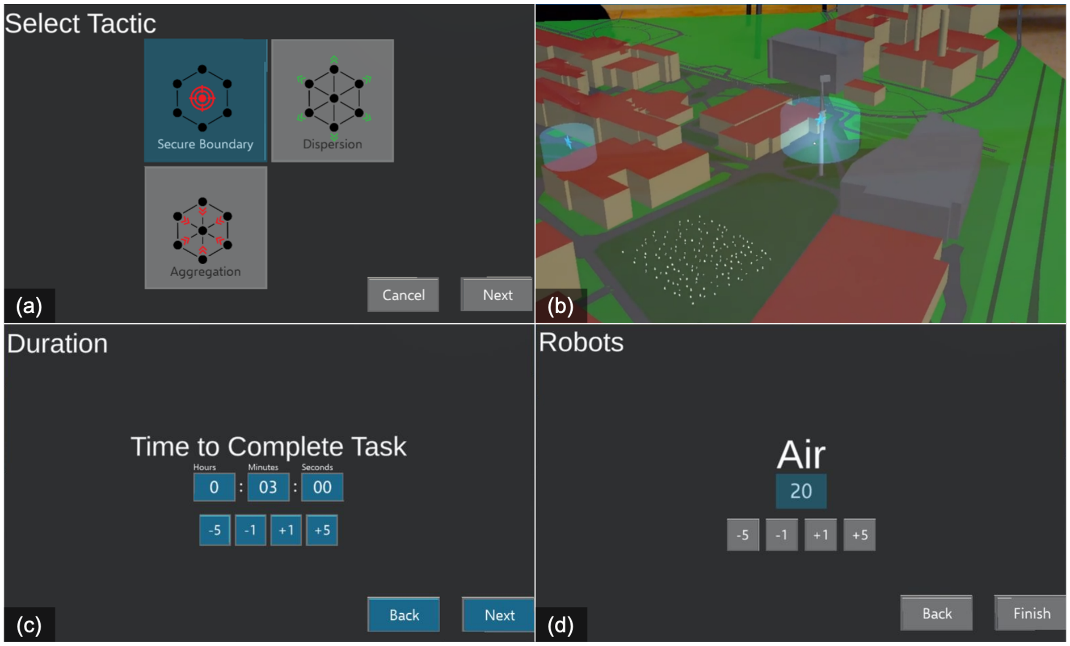

Figure 6. Tactic setup interface for SP and STF: (a) tactic selection menu, (b) tactic location (cyan star) and area (cyan cylinder) definition, (c) tactic duration selection menu, and (d) selection of the number of drones to assign to a tactic.

STR is initially presented with a similar miniaturized 3D map interface as SP (Figure 5-d), but STR also has the option to switch to a 1:1 scale first-person view that is similar to the STF perspective (Figure 5-c). The ability to switch perspectives is relevant to STR if they relocate within the operation area and require an egocentric view of swarm activity. STR can view or edit the details of an existing tactic list and add new tactics. After the tactics are finalized, the STR deploys them to the swarm by triggering the "Send to Swarm" button located at the bottom-right corner of the tactic list window in the table-top map view (Figure 5-a). This disseminates the tactics to the swarm and initiates the consensus decision algorithm. We also assumed that the STR role is responsible for making decisions on immediate events that may occur during an operation. This was represented by the autonomous creation of the Tracking Moving Target tactic by one of the drones when it detects a mobile robot that is not a member of the swarm. When this occurs, the Tracking Moving Target task is added to the task list window, and a notification message is displayed in the task detail window – both above the miniature map (Figure 5-a). The notification queries STR to either follow or ignore the detected mobile robot and waits for human input.

We assume that STF is actively involved in the mission and located within the same environment as the swarm. To suit this role, the user is presented with a semitransparent version of the 3D map overlaid upon the veridical environment and viewed through the first-person perspective. The rationale for this design is to augment the user's situational awareness of the swarm and veridical environment beyond their line of sight. This x-ray vision interface enables STF to maintain visualization of tactic status even when swarms are located inside or between buildings. The concept is demonstrated in the left half of Figure 5-b, which shows the mixed reality 3D map closely colocated with the veridical environment, which is visible through a veridical window in the room. The right half of Figure 5-b shows that the map overlay can visualize buildings that would otherwise be obstructed by a wall to the right of the window. Additionally, swarm tactic status can be visualized in the circular icons. As shown in Figure 5-c, the icon indicates that a swarm of 20 drones reached consensus and are actively implementing the Secure Boundary tactic at a rooftop in front of the user. Figure 5-c also shows the tactic target area indicated by the semitransparent cylinder.

Gesture and EMG input with haptic feedback
The α-SWAT UI application enables the SP, STR, and STF personas to interact with the swarm using gesture input via HoloLens optical hand tracking (the native Air Tap gesture) or via EMG, and provides haptic feedback via vibrotactile motors or peripheral nerve stimulation. Although Air Taps are reliable, EMG input serves as a potential alternative in field situations when users need to hold critical equipment with their hands and are unable to perform hand gestures. For EMG input, selection inputs can be triggered by contracting the finger flexor muscles for 0.5 s, which can be achieved by making a fist or tightly gripping an object already held in their hand. We used a custom modification of a K-nearest neighbor (KNN) EMG processing algorithm to decode finger flexor activation from adhesive skin-surface electrodes worn on a user's forearm (Dewald et al., 2019). Individuals with a below-elbow amputation can also contract the muscles involved in finger flexion, and these contractions can then be recorded using Intramuscular Myoelectric Electrodes (IM-IMES). EMG was recorded from eight pairs of electrodes through the Ripple EMG front end for the implanted setup and through a Touchproof adapter for the surface EMG setup. A ground electrode was placed on the olecranon of the elbow for both. A KNN regression velocity controller was trained to predict joint movement from the recorded EMG. KNN training sets were collected for three degrees of freedom of hand motion, using a previously evaluated VR hand posture matching program and custom-built Simulink model (Dewald et al., 2019). Tactile stimulation was delivered through a modified Nano2 front end to a 16-channel Composite Flat Interface Nerve Electrode (C-FINE) on the median nerve for the implanted setup (Dweiri et al., 2016; Freeberg et al., 2017). A custom MATLAB graphical user interface (GUI) was used to control stimulation parameters. Robot Operating System was used to synchronize the transport of EMG and haptic feedback over TCP/IP.

Haptic feedback was also provided to the user's hand to mitigate the risk that auditory feedback could be obscured by noise generated by the propellers of large aerial swarms or the environment. Feedback was delivered through a vibrotactile motor attached to the dorsal aspect of the index finger of a glove worn by able-bodied users. The participant with limb loss received sensory feedback from stimulation applied through implanted nerve cuff electrodes. Charge-balanced square pulses were used to elicit sensation on the palmar side of the hand between the index and middle fingers. Stimulation parameters (pulse amplitude, pulse width, and pulse frequency) were tested and selected prior to the use of the system.

4. Field Experiment Demonstration and Neural Interface Case Study

For the neural interface case study, α-SWAT was evaluated by a volunteer using implanted EMG input and two able-bodied study staff members (one using camera-detected hand gesture input and one using skin-surface EMG input) from the SP persona perspective with a simulated swarm of 150 UAVs. For the field experiment, we demonstrated simultaneous STR and STF visualizations live during FX3 with a heterogeneous hardware swarm of 40 robotic agents.

Field Experiment Demonstration of STR and STF Visualization

At OFFSET FX3, we demonstrated that α-SWAT could visualize the STR and STF persona UIs for two simultaneous human team members using live telemetry from a heterogeneous swarm of 20 aerial (Solo, 3D Robotics, Westminster, CO) and 20 mobile (R1, Aion Robotics, Berkeley, CA) robotic agents being operated by the Raytheon BBN CCAST SSI team. The CCAST team conducted several 30-minute trials using their VR-based CCAST HST interface designed for a single human supervisor (Clark et al., 2021) to deploy up to 40 robots in search of "high value objectives" placed throughout a 2.25 km^2 field experiment site. As a Sprinter team, our goal was to visualize the field experiment site and swarm for multiple simultaneous human team member personas using live telemetry broadcasts by the CCAST team during one of their trials. To prevent interference with the CCAST team's operations, our team was limited to only receiving swarm telemetry and was not permitted to transmit data to the swarm. We were also required to be in enclosed rooms just beyond the field experiment area to prevent injuries from aerial drone failures. Due to these limitations, we were not able to command the hardware swarm or have humans located among the swarm. Thus the scope of our demonstrations included only HST visualization and did not include demonstrating our distributed consensus decision-making algorithm or implanted EMG interface.

We successfully visualized the 3D map and real-time swarm telemetry of individual robotic agents for two simultaneous human team members adopting the STR and STF personas. The CCAST team provided us with a 3D map of the field experiment site generated from a drone flyover and telemetry generated from the individual GPS coordinates of all active robotic agents. The robotic agents periodically shared telemetry UDP packages via the CCAST wireless network (Clark et al., 2021). Each package included the agent's unique identification number, current position, current heading, current task, and remaining battery level.

Figure 7-a shows the miniature map and first-person (Figures 7-b, 7-c, and 7-d) viewpoints of our MR interface, showing the swarm's mobile agents relative to a 3D map of the field experiment site. In STR mode, human team members can see swarm positions as relayed by live telemetry in the context of a miniature map view (Figures 7-a and 7-b) or look toward the veridical locations of each swarm unit and see computer-generated swarm positions through interior walls (Figure 7-c). Furthermore, we demonstrated STF mode function, which visualized a 1:1 transparent 3D map and swarm positions that would otherwise be occluded by interior walls (Figure 7-c) or exterior walls outdoors (Figure 7-d). The 1:1 map was calibrated to the veridical space using the same world anchor technique described in Section 3.3. This field experiment provided a proof of concept that α-SWAT could generate innovative visualizations of live swarm operations to multiple simultaneous users from a hardware test bed both indoors and outdoors.

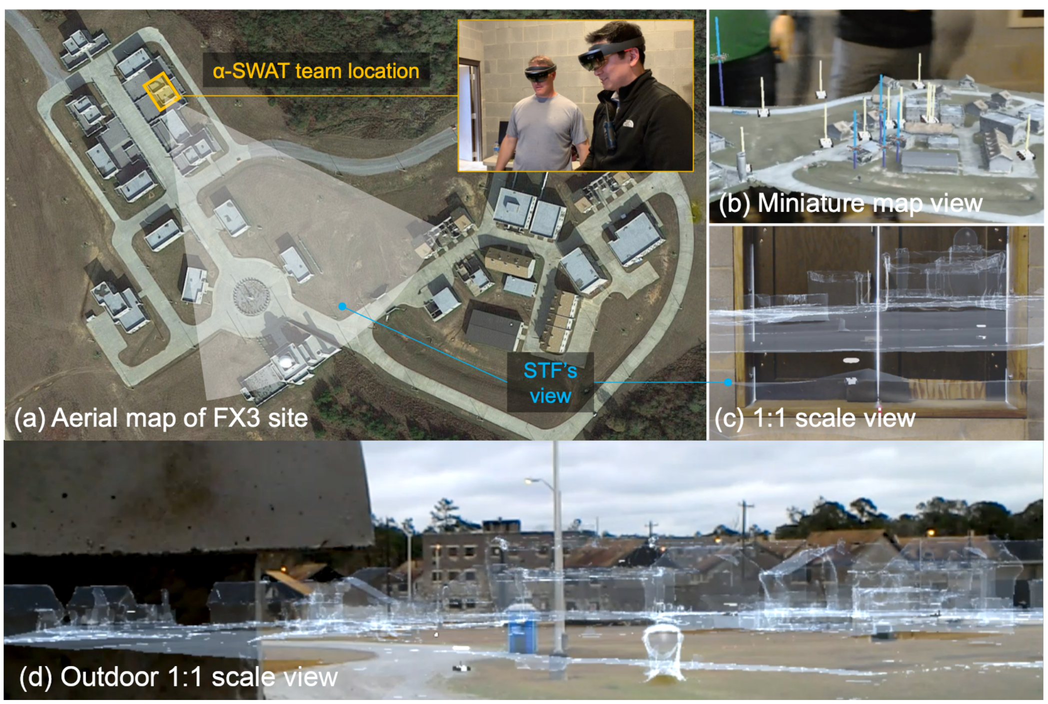

Figure 7. Overview of the FX3 site and α-SWAT team location for MR-based UI demonstration: (a) aerial view of the FX3 site with the physical location of our team highlighted in the yellow box; (b) miniature map view for SP and STR roles to visualize the entire mission site and physical locations of the swarm agents; (c) 1:1 scale view for the STF located indoors where the swarm agents and outlines of outside buildings can be seen through an interior wall, closed door, or shuttered window; and (d) 1:1 scale view for the STF from a position located outdoors with map outline visible through exterior wall on the left side of the image.

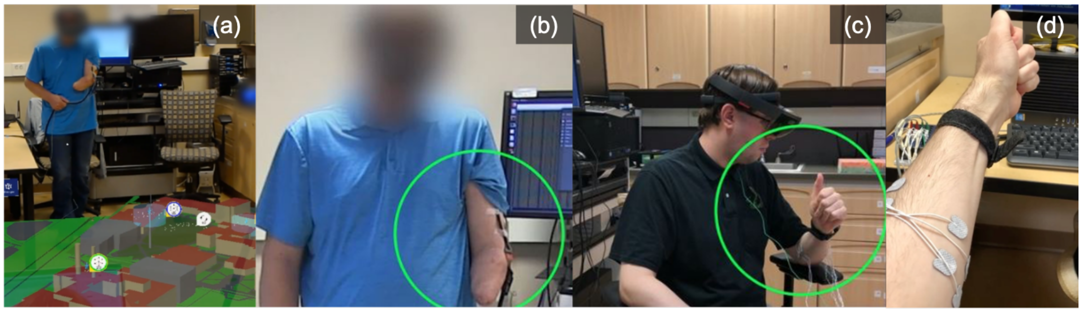

Figure 8. (a) The participant with below-elbow amputation is viewing the Swarm Planner miniature map and (b) using their implanted nerve interface to configure swarm tactics. The nerve interface also uses stimulation to provide tactile feedback. (c) An able-bodied study staff member is using (d) skin-surface EMG placed on the finger flexor muscles to configure swarm tactics. A vibration motor attached by a black Velcro wrist band applies tactile feedback.

Neural Interface Swarm Planner UI Evaluation with Simulated Swarm

After the field experiment was completed, a separate evaluation was performed at the Louis Stokes Cleveland Dept. of Veterans Affairs Medical Center. Human participants used the SP interface to plan three tactics: "Aggregation," "Dispersion," and "Secure Boundary," which were modeled after hypothetical military tasks that may involve multiple robotic agents. This served as a proof of concept that our system could be utilized by both able-bodied individuals and by an individual with an implanted sensorimotor neural interface.

Participant with neural interface and below-elbow amputation

In this case study, we recruited one male participant with a unilateral left-arm transradial amputation since there are limited participants who have this novel implanted neural interface. Our participant was implanted with two 16-channel composite flat interface nerve electrodes (C-FINEs) (Tyler and Durand, 2002; Dweiri et al., 2016; Freeberg et al., 2017) on his median and ulnar nerves, proximal to the elbow (Figures 8-a and 8-b). Additionally, he was implanted with eight bipolar intramuscular myoelectric electrodes within eight different muscles in the residual limb: pronator, flexor carpi radialis, flexor digitorum superficialis, flexor carpi ulnaris, supinator, extensor carpi radialis longus, extensor digitorum, and extensor carpi ulnaris. All data were collected in one day during a single session spanning three and a half hours. The participant used either a VR or MR headset on two prior occasions to view and control a prosthetic hand. However, this was the participant's first time using an MR headset to interact with a graphical user interface. All study devices and procedures were reviewed and governed by the U.S. Food and Drug Administration Investigational Device Exemption, the Cleveland Department of Veterans Affairs Medical Center Institutional Review Board, and the Department of the Navy Human Research Protection Program. Informed consent was obtained from the participant.

Haptic feedback and control setup and evaluation scenario

In order to make selections within the virtual interface, the participant was instructed to contract their arm in a manner that would correspond to closing their hand. Therefore a single degree of freedom corresponding to the hand closing was used to select buttons, drop pins, and select an area within the virtual interface. EMG threshold and time threshold parameters were tested and set prior to the start of the simulated evaluation scenario. EMG threshold was defined as the minimum contraction effort needed to issue a command, and the time threshold controlled how long the participant would need to sustain a muscle contraction above the EMG threshold. Able-bodied study staff went through a similar EMG threshold detection process, but adhesive skin-surface EMG electrodes were placed over the flexor digitorum muscles that flex the fingers. The EMG calibration for each participant took 1–1.5 hours. This calibration process involved choosing fixed controller values, asking the participant to perform the finger flexion gesture to click a button with those values, and then asking them how difficult it was to select the button and how much effort it took (revising if necessary). Once final values were chosen, participants activated a UI button several times to verify the consistent response. After the initial setup, the calibration could be reused in later sessions after minor adjustments and reverification, which typically took 5–20 minutes.

Tactile sensation was stimulated on the index and middle fingers (Figures 8-a and 8-b) when the participant finished compiling the list of three tasks and selected the "Send to STR" button. Haptic feedback for able-bodied study staff was provided by a small vibrotactile motor attached to the human team member's wrist using a Velcro band (Figures 8-c and 8-d). Stimuli for the participant with limb loss consisted of biphasic, charge-balanced, 1-second trains of rectangular pulses delivered to the implanted electrodes. We used 250 μs for pulse width and 100 Hz for pulse frequency, and all stimulation parameters were held constant throughout the experiment. Pulse amplitude was selected based on participant feedback to ensure that the intensity of the elicited sensation was above the threshold while still comfortable and that the tactile feedback could still be felt while contracting the arm to make selections. Stimulation was delivered through a single contact on the C-FINE electrode.

Following the setup of haptic feedback, EMG control, and the HoloLens headset, the participant was trained on the system and simulated the scenario for approximately 30 minutes. The participant watched a PowerPoint presentation containing screenshots of the virtual map and the list of steps he would be asked to take in the same order that he would be following to become familiar with the virtual environment. A screenshot visualized the part of the interface to focus on and the expected tasks he would need to make a selection for each step. The participant was walked through this PowerPoint twice before performing the mission scenario. Once the participant donned the HoloLens headset, he was allowed to practice adding the "Secure Boundary" tactic to the Task Planning list, which entailed selecting a location on the map, defining the task duration, and selecting the number of drones involved. He then practiced selecting a location for the "Dispersion" and "Aggregation" tactics to become more comfortable dropping a pin and then defining the area around the pin. Following training, the participant performed the mission scenario three times, with a break of at least 15 minutes between each repetition. An experimenter followed along and read instructions detailing the next step the participant would need to take after making a selection. The time for the participant to complete each trial of the mission scenario was recorded, starting when they selected the "Task Planning" button before adding any tactics and ending when they clicked the "Send to STR" button after compiling the full task planning list. In addition, verbal responses were collected through unstructured interview questions about their experience.

Results and discussion

The average time necessary to complete each trial was 2 min 53 s for the participant. Completion time decreased with each repetition, with the third trial taking 2 min 32 s (Figure 9). These completion times were comparable to that of our able-bodied study staff responsible for developing the interface and well-versed in its controls. The times for the study staff ranged from 1 min 41 s using the "Air-tap" control to 2 min 11 s using surface-EMG control (Figure 9). This demonstration showed that the setup expands the usability of the HST interface so that it can be used efficiently and intuitively by humans with limb loss. The HoloLens headset allowed the participant to navigate through the interface without hand or arm motions, and the implanted EMG setup allowed interaction with the interface without needing a hand. Prior human-swarm interaction and teaming interfaces generally assume a participant has a hand with which to make hand gestures or hold a controller. However, the implanted EMG system gave our participant the fidelity of someone with an intact hand controlling the same system. The technology used here could also enable humans without limb loss to use their hands to hold mission-critical objects without limiting their ability to interact with the swarm. This technology could also be expanded to provide a means for interacting with any interface that usually requires a hand.

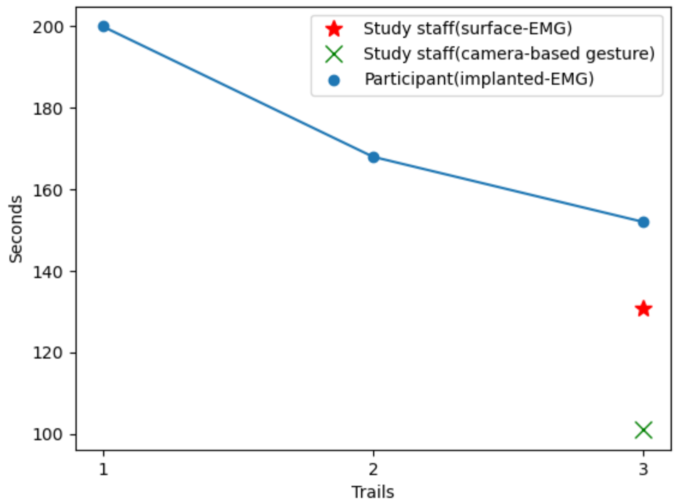

Figure 9. The completion times of the simulated swarm tactic planning experiment for our participant with limb loss and study staff.

After the three trials, the participant was asked his thoughts about the interface. He replied that he enjoyed the tactile feedback and that it provided good confirmation when he selected a button. Since tactile feedback was provided only when the final "Send to STR" button was selected, he also added that he would have liked tactile feedback with every button selection throughout the trial as confirmation. This study, therefore, showed that tactile feedback was still useful even though it was not linked to the visual image of a hand and made the setup easier to use. In addition, the participant felt that the trials got easier when he adjusted his strategy to focus on the virtual environment while ignoring the veridical environment. This may have been due to the role he was playing, as the SP did not need to interact with the veridical environment during the experiment. Introducing this interaction and seeing how this changes the participant's feedback and the cognitive burden would also be an interesting future experiment. The participant did express that the MR headset was less disorienting than previous virtual reality headsets he had tried in the past. This allowed him to easily walk forward to get a better view of other parts of the map. Overall, he commented that the interface was "a pretty usable, easy system to use" and that "as much as I've played with a mouse in my life..., I would probably enjoy this more. It's more interactive, especially the feedback." The participant's feedback was consistent with some of the feedback collected from our study staff as a part of the development process. Specifically, using EMG "as a button and the HoloLens as a display was a natural way to manipulate the environment" and "the system is easy to become familiar with and develop a routine for."

Several opportunities for improving the system were identified during our development that should be addressed in future work. Specifically, the system's scalability needs to be systematically investigated regarding the number of users and swarm robots. The current work only captured HST metrics for the SP interactions. Future work will require additional focus on the performance of the STR and STF roles. Additionally, although the multi-persona interface has been implemented and demonstrated functional in simulation, only passive observation of a robotic test bed at the field experiment was possible due to safety restrictions. In future work, field experiments between all three personas with a robotic testbed need to be studied. Furthermore, the skin surface EMG acquisition methods need to be revised to be suitable for independent donning/doffing and field use. The long duration of the current EMG gesture detection calibration method may limit the scalability of the current approach to a broader population of users and should be reduced in future work. Existing wireless EMG acquisition systems may be suitable for future versions of our HST system. Although rare in the literature (Vovk et al., 2018), one of our study staff experienced motion sickness using

HoloLens. Therefore future experiments may need to screen for individuals who experience motion sickness using HoloLens.

5. Conclusion

In this work, we developed an inclusive MR-based HST interface consisting of the swarm simulator and the multimodal, configurable UI that adapts to the needs of multiple simultaneous users with different roles, physical capabilities, or preferences. The system supports three specific roles (i.e., SP, STR, and STF), each with different levels and types of activities supported by the unique UI design. UI modalities and the number of human team members who can interface with α-SWAT are scalable and configurable. We selected MR-based visualization and two ways of the sensorimotor interface to demonstrate the system-level integration and its configurability. The swarm simulator has embedded task allocation and swarm algorithms corresponding to a few commonly used swarm tactics to support various simulations, physical experiments, and field experiments. We verified that our system could visualize a veridical robotic swarm to multiple humans at DARPA OFFSET FX3. In addition, we conducted a case study to demonstrate a proof-of-concept for a person with an implanted neural interface and upper limb amputation. The result showed that this participant could perform HST tasks at a rate comparable to able-bodied expert users. The participant's responses also identified ways to improve immersion for human team members, warranting future refinement as described above. These preliminary evaluations indicate that α-SWAT represents an important first step that will inform the future development of future HST interfaces. Future work may involve an extended human subject study to further investigate the usability, differences among the human team member roles, learning curves, and fatigue. Additional field experiments are needed to further improve the UI design and streamline the HST activities.

Acknowledgments

The views, opinions, and/or findings expressed are those of the author(s) and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government. This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA) through DARPA Contract No. N660011924023, under the OFFSET Sprint-3 Program. This manuscript has been classified under Distribution "A" (Approved for Public Release, Distribution Unlimited). The 3D map used at the field experiment (Figure 7) was provided by the CCAST Raytheon BBN team.

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How to cite this article: Zhao, C., Zheng, C., Roldan, L., Shkurti, T., Nahari, A., Newman, W., Tyler, D., Lee, K., & Fu, M. J. (2023). Adaptable mixed-reality sensorimotor interface for human-swarm teaming: Person with limb loss case study and field experiments. *Field Robotics, 3*, 243–265.