Drones in Firefighting: A User-Centered Design Perspective

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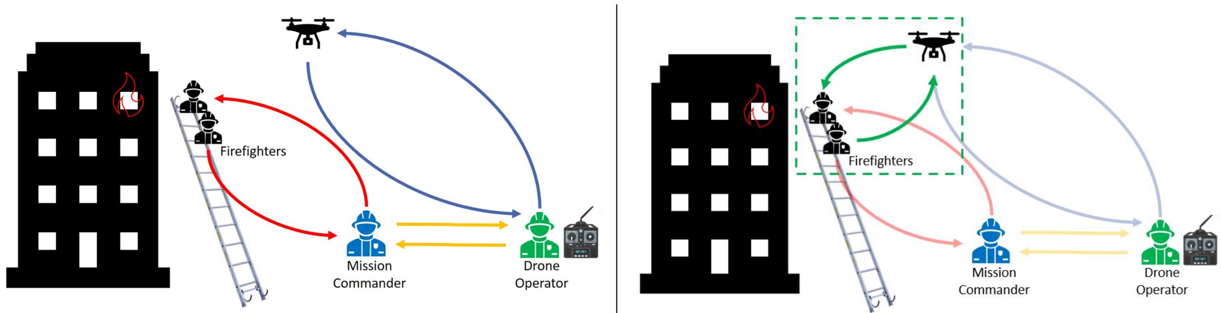

(a) Current Interaction Strategy

(b) Proposed Interaction Strategy

Figure 1: Drones in Firefighting: (a) Current interaction strategy with three communication channels described with arrows: (Red) Between the firefighters and their commander. (Yellow) Between the commander and the drone operator. (Blue) Between the drone operator and the drone. (b) The proposed interaction strategy (Green) envisions providing a direct interaction technique between the firefighters and drone (Green box).

ABSTRACT

This work presents a user-centered perspective on the integration of semi-autonomous drones in firefighting. We first present the outcomes of an interview with the leading officers in Israel, which revealed opportunities and barriers in drone integration, as well as current usage and future needs. We envision a future where firefighters and drones can directly communicate with each other and propose the use of gestures in collocated environments. We then present the results of an elicitation study with operational firefighters (N=9), which resulted in a set of tasks for drones and matching user-defined gestures that can be performed in highly constrained environments. This research opens the space for future collocated human-drone interaction in emergency response and other complex professional settings.

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CCS CONCEPTS

• **Human-centered computing → Interaction techniques**; **Gestural input**; **Empirical studies in interaction design**; **Systems and tools for interaction design**; • **Computer systems organization → External interfaces for robotics**.

KEYWORDS

Human Drone Interaction; UAV; Firefighting; Elicitation Study; Human Machine Teaming; Collocated Interaction; Harsh Environments.

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1 INTRODUCTION

Drones are steadily becoming ubiquitous [47] and are used in a variety of professional environments such as in the police forces and military [14, 18], in search and rescue [4], and firefighting [38, 56]. They represent a novel type of mobile technology that professionals bring with them and activate when needed. Recently, we are seeing a technological shift with increasing levels of autonomy [4, 10]; with drones that can now perform tasks such as indoor navigation, surveying, filming, or mapping [20, 21, 28, 35, 40] autonomously using embedded sensors. This shift towards autonomy creates new interaction paradigms where drones become fully mobile devices that can interact with people at any time and location. In firefighting, prior works envisioned that drones will, over time, support various missions including detecting, monitoring, and extinguishing fires [22, 36, 38]. Indeed, drone technology offers unique opportunities to firefighters by bringing bird's eye view situational information, in real-time and at a low cost, which can reduce the risk to human life and properties. We imagine that, in the future, drones will not only support firefighters from afar, but also join them in their missions, helping them navigate inside a building on fire, or even guiding them through smoke. Yet, this vision will require people and drones to work closely and safely together.

Nonetheless, the integration of drones in human environments is not trivial, and neither is the introduction of technologies in emergency response. Firefighting presents incredibly complex challenges in terms of the "physical risk, psychological state, and operating conditions" [23]. Operating conditions of firefighting missions, which are referred to as *"harsh environments"* and can typically include low visibility, noise, open fires, smoke, and extreme temperatures, which furthermore require firefighters to wear heavy protective equipment.

In this work, we propose to investigate, first, how drones are being integrated into firefighting teams; and second, to elicit gestures that would enable collocated interaction between firefighters and future autonomous drones. The field of collocated Human-Drone Interaction (HDI) is rapidly growing, and prior works have investigated various interaction techniques. Our analysis of the literature shows why gestures are best suited in this context. Yet, while gestures have been investigated for collocated HDI with lay users [7, 12, 30, 32, 34], the unique constraints of the firefighting environment require additional work to fully understand which gestures can and should be used in their professional context. It is then primordial to further examine gestural interaction for collocated HDI with firefighters, who are best suited to comprehend the constraints of their environments.

In this work, we take a holistic approach to understanding current and future practices for drones in firefighting. We conducted a first study where we interviewed the leading R&D firefighting officers in Israel, which allowed us to identify the current and future usage of drones, as well as the unique constraints and specific needs of firefighters. Based on our findings and our literature review, we opted for a gestural interaction strategy. We then conducted a second study with operational firefighters (N=9) which consisted of a focus group followed by a gesture elicitation study. The results led to a set of tasks and matching user-defined gestures.

Our results contribute a novel perspective and understanding of how drones can be integrated into firefighting, as well as a set of gestures for specific tasks where drones are needed in firefighting. Our findings further inform future researchers and practitioners on human and socio-technical factors to consider when integrating drones in emergency response.

2 RELATED WORK

In the following section, we will review the related literature on the use of ground and aerial robots in firefighting, on existing collocated human-drone interaction techniques, and prior gesture elicitation studies with drones.

2.1 Ground and Aerial Robots in Firefighting

Firefighters typically operate in environments characterized by high temperatures, smoke, and low visibility, which are referred to as *"harsh environments"*. These have been defined as environments that are "hazardous to agents (human or robot etc.) within it [...] characterized by high levels of radiation, high explosive risk, extreme temperatures or pressures, and lack of oxygen." [54]. Additional characteristics include "unknown, unstructured, dynamic, cluttered, hazardous and/or limited in resources (such as the availability of communications, GPS and visibility)" [53]. As such, these environments present unique challenges for Human-Robot Interaction (HRI) and for integrating mobile technologies more widely (e.g., sensing next to open fire sources or dealing with dynamic obstacles and faulty sensors [6]).

The HCI community has been investigating technologies to support firefighters [11, 24]. The literature suggests using ground and aerial robots to aid firefighters in various missions, such as in search and rescue [29], detecting and extinguishing fires [27, 46], mapping, and detecting gas in both indoor and outdoor environments [19, 40]. Yet, prior work investigated the potential of ground and aerial robots for firefighting missions [42] and revealed that drones were hardly used to firefighting missions; and further showed that firefighters found the drones' relevance for their purpose to be rather low. The researchers mentioned their findings may be explained by the limited range and operating time of drones at the time (2016), and by the additional resources required to control drones. Since then, promising works have shown that drones can benefit firefighting missions by providing visual access to low visibility areas, increasing safety to firefighters during emergency missions, optimizing the data gathering processes, time-saving, and reducing human error in inspections of a zone [38]. Further work investigated the use of drones in emergency situations [26] by interviewing firefighters and 9-1-1 callers, and showing that both user groups felt positive about drones. Agrawal et al. [2] then proposed an interface for search and rescue drones that provide added situational awareness to firefighters. Finally, earlier this year, Roldán-Gómez et al. [39] interviewed professional firefighters and concluded that drones have the potential to improve firefighters' efficiency and safety in forest firefighting, providing a bright outlook for the future of drones in firefighting.

Yet, in all of these works, the drone is considered as a remote control technology. Since prior work has shown that as systems increase in autonomy, workload decreases [17]; we suggest that autonomous drones could further support firefighters in their mission. In particular, we focus on situations when firefighters and drones are collocated. To help us understand which type of interaction is best suited, we analyze prior work on collocated HDI.

2.2 Collocated Human-Drone Interaction

Various interaction techniques have been proposed in the literature for collocated HDI such as using a remote control [3], brain-computer interface [25], wearable technology [15] on the user, speech using a ground station for the recognition side [9], or by combining multiple modalities such as speech, body position, and hand gestures [45]. Other techniques proposed direct interaction with sensors embedded on the drone by detecting the user's face poses and hand gestures [7, 30, 32, 34] or touching the drone [1, 16].

Based on the review of existing collocated interaction techniques and input modalities, we chose to focus on gestures as a promising approach for a drone to interact with firefighters. Our reasoning is multi-fold: 1. Gestures have been described as the most natural interaction technique in collocated HDI [7, 12, 33], where prior research showed that participants preferred direct communication with gesture and voice over other techniques, and with high agreement on gestures; 2. Drones usually carry a camera, so no additional equipment would be needed for sensing, and gestures are easier to recognize than face poses when wearing a helmet. This will also enable the drone to interact with any firefighter and not only with the person holding the token of control (e.g., wearable device); 3. Remote controls are incompatible because they limit the operators' ability to perform other tasks [24], in addition to being harder to use and less intuitive than gestures; 4. Other interaction techniques, such as voice, may not work with sensors embedded on the drone, and may fail in this environment, for example, because of the noise of the scene and the mask that firefighters wear.

While gestural interaction may be less precise than remote control [47], we envision that semi and fully autonomous drones will not require the precise control required to maneuvre a drone, but instead a more general understanding of high-level commands. To design appropriate gestures in HDI, prior works used a gesture elicitation methodology [7, 12, 34, 43], which we further elaborate on in the next subsection.

2.3 Gesture Elicitation with Drones

The gesture elicitation methodology is increasingly being used by designers and researchers to identify appropriate user-defined gesture sets for mid-air gestures across various applications [50]. Villarreal-Narvaez et al. [49] surveyed 216 gesture elicitation studies including from the fields of Human-Robot and Human-Drone Interaction (HRI/HDI). Prior works that dealt with gesture elicitation in drones first explored how lay users naturally interact with them and focused on low-level commands (e.g., stop, land, follow, or fly lower) [7]. The methodology was replicated in China [12] and showed that, while participants used different gestures, there was a high agreement in the choice of gestures [12]. Additional works investigated further gestures through elicitation for drone navigation [34] and to interact when running [43]. All of these works have been conducted with lay users for the everyday environment, with a focus on low-level commands.

While future autonomous drones will require less precise control, it is still unclear how to convey high-level commands to a drone, using mid-air gestures. In addition, the firefighting environment is a highly constrained and harsh environment, with the users – firefighters– who are professionally trained personnel. We propose to run a gesture elicitation study to identify the appropriate gestures for firefighters to interact with drones in collocated situations. We will emphasize the work on high-level commands specifically designed for users in harsh and highly constrained professional environments.

To understand the current and future uses of drones in firefighting, the constraints of the environment, and how firefighters could interact with drones, we conducted two in-situ user studies. In the first study, we conducted a need-finding interview with the leading experts in the country responsible for the use of drones (N=3). This study aimed to understand their point of view as decision-makers and to identify scenarios of use and their future vision for drones. In a second user study, we conducted a gesture elicitation study with active firefighters (N=9) at their fire station.

3 NEED-FINDING INTERVIEW

We conducted a semi-structured interview at the firefighting forces headquarters of *Country name blank for review*. Our goal was to understand the current usage of drones in firefighting and existing barriers to the integration of drones, gain insights about future needs, and identify scenarios of use. We recruited participants by contacting the head of research and development at the National Fire and Rescue Authority who helped us identify the leading experts responsible for the introduction and use of drones and other new technologies. We conducted the interview with three participants, all senior officers (see Table 1). Each participant volunteered to participate in the interview which was audio recorded, in addition to notes taken by the research team. The sections below describe insights gathered in the interview.

3.1 Current Use of Drones

At the time of the interview, there were four drones owned by the firefighting forces nationally, and only one certified operator, the head of aerial firefighting. To answer the operational need for drones, the firefighting forces outsource external drone service providers who can, for example, survey villages close to forested areas on hot days, to detect fires at early stages. Experts have mentioned two main environments of use: outdoors with wildfire or wild urban fires and indoors in high-rise buildings, tunnels, and underground parking lots. The drones are currently used almost entirely for outdoor scenarios, but efforts are being conducted to integrate drones indoors. All experts agreed about the advantages of using drones in firefighting missions. The drones are currently used with one main purpose: as a flying camera, showing a live feed, taking pictures, and videos. In terms of tasks, experts said the main challenge in firefighting missions is **situational awareness**, meaning "to know what is going on", or more formally, "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [13], and that is the main task they use a drone to help them with. Drones can be sent upfront to provide additional information before people get on the scene and

Table 1: Table of expert participants including their job description, experience in this role, and additional remarks.

Role	In role	Remarks
Head of aerial firefighting and drones operation in firefighting forces	24 months	Only drone operator in the firefighting forces. Prior equivalent position in the police forces
Head of operational research and development	6 months	Previous experience working with drones and information systems in the army
Intelligence officer of the firefighting forces in charge of wildfire firefighting theoretical models	12 months	Prior academic with PhD in wildfire fighting

they can monitor what is happening in real-time. The drone allows the firefighters to better prepare for the situation, support them in conducting their missions, with the potential to reduce the risk to people's lives. The experts described a recent example of a forest fire near a village. After airplanes finished their part of fire extinguishing, a ground unit kept fighting the fire with the assistance of a drone that was then launched to detect active fire spots. They described another example, where a drone was used to take pictures and videos of a wildfire before the firefighting airplane arrived. The National Fire and Rescue Authority is working at expanding the number of drones and the tasks drones can fulfill. One of the experts mentioned a drill conducted as part of the R&D effort where they tried using a drone to extinguish a fire. The test was conducted with a large agriculture drone carrying water as part of a 5 kg payload. Unfortunately, this attempt was unsuccessful as the drone sprayed water too slowly and the wind generated from the propellers made the fire stronger instead. This shows the firefighting brigade's need in having novel technologies that can support them in their work. In another drill, a drone was used to enable the commander on the ground to monitor the fire as well as his team on a crane by a tall building. The drone operator stood beside the commander and the drone companion app on a smartphone showed the video stream. This shows that a drone can be used as part of command and control, helping troops on the ground by increasing their situational awareness.

3.2 Barriers to the Integration of Drones

The experts have mentioned various barriers to the integration of drones. The certification to operate remote-controlled drones is delivered by the civil aviation authority (equivalent to FAA). Getting a drone certification currently involves a process similar to the theoretical part of getting a flying license, which is lengthy and appears to be excessive compared to the skills required to fly a drone. This legislation has been a barrier to the number of pilots in the firefighting forces and at the time of the study, several firefighters were in the process of getting their license. The experts also pointed out technical limitations around the use of drones. For example, indoors, the smoke generated from fires can disrupt the visibility beyond 1 meter, which calls for better cameras, such as thermal instead of RGB; and the lack of a GPS signal raises the need for other sensors to position the drone and keep it stable. One expert further reported how difficult it is to operate in such an environment and that a connection loss can occur between the drone and the controller if they are separated by more than one floor. This shows some of the limitations and risks posed by having a drone operator, where the lack of connection between the remote control and the drone could prevent safe use of the drone. We suggest that direct human-drone interaction with a semi-autonomous drone would help overcome such issues.

> *"if something happens to the drone, then it's ok, it can go in front of me. A lot of times, firefighters were killed because they didn't know what's in front of them"*
>
> *"eventually, I don't think people will risk [their lives] with something that can be done without people"*
>
> *"we have two main scenes, one is wildfire or wild urban fires [outdoors], and second high rise buildings, tunnels and underground parking lots [indoors]"*
>
> *"you also need to be a very good pilot, because it is hard to operate a drone indoor"*
>
> *"the main thing, the main issue, is to get situational awareness. That's the main thing before anything else"*

3.3 Human-Drone Interaction

The normal procedure is for the on-site commander to allocate tasks to the drone via the operator, standing by their side, outside of the danger zone. The operator remotely controls the drone within their line of sight. Yet, experts reported that when the drone operator is part of the mission briefing, team members may ask him for specific requests directly through the walkie-talkie, for example, to gather information from a specific area, or to find fire spots. There are currently no strict rules about the chain of commands regarding drone operation. Figure 1a illustrates the current interactions and information transfers between firefighters and a drone. There are three channels of communication:

- *(Red)* Firefighters-Commander: Firefighters ask their commander for specific information to be gathered by the drone, such as information about a fire out of their line of sight. The commander gathers information (Yellow) and shares insights with the team.
- *(Yellow)* Commander-Operator: The commander conveys to the operator what he needs from the drone. The operator pilots the drone accordingly (Blue), so that both the commander and the operator can view the live feed on a smartphone and interpret the information.
- *(Blue)* Operator-Drone: The operator pilots the drone using a remote control and gets real-time feedback on the drone's condition as well as the live feed from the camera.

This current interaction strategy between the firefighting team and the drone is complex. It delays the execution and response time

Figure 2: Firefighting equipment including helmet, jacket, trousers, and gloves.

in a volatile environment, can introduce both human and machine errors, and it involves added workload to an already highly stressful situation. Moreover, the commander is receiving raw videos that need to be interpreted and analyzed in real-time over the course of the mission. Our experts pointed out that this is a demanding and difficult task. In our work, we propose to streamline the current interaction by enabling direct interaction between firefighters and a semi-autonomous drone (see *Green* arrows in (Figure 1b)), so that, in the future firefighters will be able to directly communicate their needs to the drone and receive feedback in return. This concept does not change the current command structure, or the current role of the drone pilot, but instead imagines the semi-autonomous drone as part of the operational firefighting team. We note that this type of direct interaction has been suggested as the way forward when interacting with autonomous drones in collocated contexts [8].

In terms of equipment, while the drone operator does not wear gloves or a helmet as they are not actively firefighting, the experts expect that any firefighter that will need to interact with a drone will be wearing their full equipment on (including gloves and helmet, see Figure 2), ready to fight a fire. This will create additional consideration and constraints when designing suitable interaction techniques for active firefighters in full uniform.

3.4 Future Vision of Drone Usage

Experts said they would like to broaden the use of drones in firefighting forces and to have at least one drone in each big fire station, as well as a few operators to cover several shifts. They would like drones to cover both indoor and outdoor missions, as well as to help them extinguish fires.

"The vision is that we won't need to risk firefighters' lives at all"

Regarding future scenarios of use, experts focused on the need for increased **situational awareness** and suggested future missions such as: detecting and analyzing the main and secondary spots of a fire, such as identifying their locations, their number, and the type of fuel. In addition, the drones would identify information about the firefighting forces on the scene, and lastly, search and locate civilians in need or immediate danger. Regarding future interaction strategies, experts suggested voice, gestures, or the combination of the two as the most intuitive techniques for interaction under pressure and high mental and physical workload. When asked to envision feedback from the drone, experts said they would like the drone to give processed data, such as the number of fire spots, or the number and location of survivors, instead of the current raw images and videos. Finally, experts also discussed swarms of drones. According to them, one of the next steps after integrating single drones into firefighting missions would be to scale up the effort by integrating swarms of drones that can cover more ground and gather more information.

"Another use of future drones or robots that we would want is inside buildings, especially parking lots, where you have a lot of smoke, and no GPS, we would want the drone to map the area, search for survivors, come back to me and take me to the survivors"

"you don't know where the fire is exactly, how many people are trapped, where, what kind of fuel there is and how the fire is going to spread. If I knew everything, it would be easy to overcome the fire"

"If the drone could give me the processed information, for example 4 people are there, 1 is dead, etc. I would prefer it. Thinking under pressure is hard"

"If I'm thinking about a group of drones, I imagine that I control the group, and not one specific drone, and then the group coordinates the action within itself"

In this interview, we uncovered how drones are currently used in firefighting and what interaction strategies are in place to use them in these particularly high-pressure environments.

Our next step was to meet with operational firefighters to perform the elicitation study related to gestural interaction in collocated human-drone interaction within their professional context.

4 GESTURE ELICITATION STUDY WITH FIREFIGHTERS

The second user study aimed to understand how operational firefighters themselves envision interacting with a drone and, in particular, what tasks they would like the drone to perform and what gestures they would prefer to use to interact with the drone (see Figure 3). We opted for using participatory design practices and divided the study into two parts: a focus group followed by a gesture elicitation study. The idea was to use the focus group to bring forth firefighters' current work practices and gain insights on how they use or envision using drones, as well as build trust between them and our research team. The second part of the study consisted of a gesture elicitation study (e.g., [7, 51]), in which the goal was to understand the firefighters' existing physical and mental constraints in addition to gathering user-defined interaction preferences. We opted for this methodology due to the sparse literature on gestural interaction in harsh environments.

4.1 Elicitation Study Protocol

Elicitation studies can take different forms [49] depending on factors such as the technological readiness of the investigated device or interaction. In elicitation studies, end users are asked to propose a gesture (*symbol*) to generate a desired effect (*referent*). We designed our study so that the choice of referents would be based upon contextual understanding from the discussions of the focus groups. As such, the referents (i.e., drone tasks) were elicited in the focus group, so that the firefighters themselves decided on the tasks drones could perform according to their needs. The procedure used in the elicitation part of our study is based on the work of Rädle et al. [37].

One limitation of gesture-elicitation studies is that users often choose gestures based on legacy bias from prior technology. With drones being so recent in collocated interaction, it is unclear where the legacy bias would come from, although prior work suggested that people tend to interact with drones as they would with people and animals [7]. To reduce the risk of legacy bias in elicitation studies, Morris et al. [31] proposed three additional techniques: *production*, *priming*, and *partner*, which we included in our methodology. We used the *production* technique by asking participants to generate two to four symbols (i.e., gestures) for each referent (i.e., task) before choosing their favorite. We then employed *priming* by asking one of the participants to wear his protective equipment during the study. All participants were asked to think about the constraints they have to work with when actively fighting a fire. The firefighter in gear demonstrated the use of the equipment and the gestures suggested by his teammates. We used *partners* by conducting the study with a group. That choice was two-fold: 1. firefighters do not work individually, so drones would be integrated within a team – note that our study participants were all members of the same team –; 2. we wanted to collect as many inputs and insights as possible in the process of choosing referents and gestures, and a group setting enables participants to build upon each other's ideas in a fruitful manner. Once the gestures were demonstrated, participants were asked to agree on a preferred gesture as a group task by task. Once the gesture was agreed on, we measured each participant's individual agreement towards the group's choice (as in Rädle et al. [37]).

4.2 Participants

We conducted the study with 9 male volunteers, all active firefighters from the same fire station. The participants' ages ranged from 31 to 55 y.o. ($\mu = 42.2, SD = 7.5$). All of them were highly experienced with 8 to 32 years of firefighting service ($\mu = 17.8, SD = 8.3$). Three of the participants had already used or seen drones in firefighting. The nine participants in the second study are not the ones who have participated in the first study.

4.3 Procedure

The user study was conducted at the fire station. Participants signed consent forms at the beginning of the focus group. The elicitation study was audio and video recorded. Participants sat around a table with two members of the research team (see Figure 4). After a short introduction, we conducted the focus group, in which we asked questions and encouraged conversation around two main topics: tasks that autonomous drones could perform to support firefighters in their missions and constraints and limitations to body gestures in the firefighting context. At the end of the focus group, we identified 4 drone tasks that were agreed upon by all participants, and proceeded with these tasks for the elicitation part of the study.

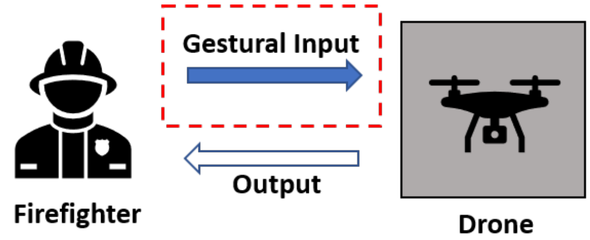


Figure 3: Two information channels are used in the collocated interaction between a firefighter and a drone. The goal of the elicitation study was to determine appropriate gestural input to the drone using user-centered methodologies.

The elicitation part started after participants took a break. The process of the gesture elicitation study was as follows: First, the researchers said each task aloud. We assumed the tasks (referents) were well understood since they were generated by the firefighters themselves earlier in the day. Second, participants were prompted to generate 2 to 4 gestures (at least 2) for this task that would be compatible with their environmental constraints. Third, they reached an agreement, as a group, regarding the chosen gesture for the specific task (i.e., they elected a favorite gesture amongst all the suggestions given for each task). Each time a gesture was chosen and matched to a task, participants were asked to individually fill out a questionnaire rating how well they understood the task, their agreement with the group's choice, and the difficulty to suggest a gesture for the specific task (7-point Likert scales). At the end of the study, participants filled out a questionnaire regarding the overall understanding of what they had been asked to do and how free they felt to express their ideas and suggestions.

4.4 Results

We present the results of the focus group and gesture elicitation study divided into four topics: constraints of the firefighting environment, tasks for drones, gestures, and additional interaction considerations.

Constraints. Participants mentioned wearing heavy protective equipment including a jacket, pants, helmet, mask, and oxygen tank weighing around 8 kg. Besides their equipment, depending on their task and mission, they may use additional gear, such as a thermal camera attached to their equipment, a water hose, a crowbar, and other special equipment. Participants mentioned that their typical environment includes smoke and lacks visibility. They also mentioned the important time pressure and stress of firefighting *"when*

Figure 4: Illustration from the gesture elicitation study. The participants sat around a table with members of the research team. All participants proposed gestures which were demonstrated by the firefighter wearing his protective equipment (on the right).

you arrive at a building on fire, you have no time to breathe, you need to storm in". In terms of especially complex environments, participants mentioned parking lots, industrial and high-rise buildings as important environments in which a drone can provide much-needed help, similarly to the suggestions made by the experts in the first user study.

Drone Tasks. All participants agreed that drones have a high potential to help them with their missions. When asked what tasks they would like a drone to perform to help them in their missions, their first reaction was that they need the drone to help them better comprehend the situation at hand. We found that all subsequent mentioned tasks stemmed from the need for situational awareness. This finding is in par with our previous study (section 3) which highlighted the pressing need for situational awareness and real-time information. During the focus group, participants mentioned various tasks and scenarios for drones. Four tasks were deemed the most important are presented below:

- **Mapping.** They envisioned sending the drone to map a floor or even an entire building, finding out how many rooms are inside a building, what the structure of the building looks like, and creating a map of it.
- **Identifying Hazardous Materials.** They proposed the drone could identify the type of hazardous material (such as gas or chemicals), and the source and size of the leak, which is a scenario they encounter in industrial buildings.
- **Detecting Fires.** They proposed the drone could identify fire spots. This is in line with current drone usage in the country identified in the need-finding study.
- **Finding Survivors.** They suggested sending the drone to search for trapped civilians or people otherwise in danger. They would like the drone to gather information on the number of people as well as their condition and location. They proposed the drone could directly provide help to citizens who fell into holes or deep tunnels. The firefighters further mentioned a situation that they referred to as "fear for human life and aid to civilians". This corresponds to situations where there is a concern for civilians, who are locked in their homes and are not responding to the door, who usually were not seen by their relatives or neighbors who called the firefighters to break in. Participants have mentioned that a drone could fly inside the apartment through a window to help them conclude whether they need to break into the apartment or not.

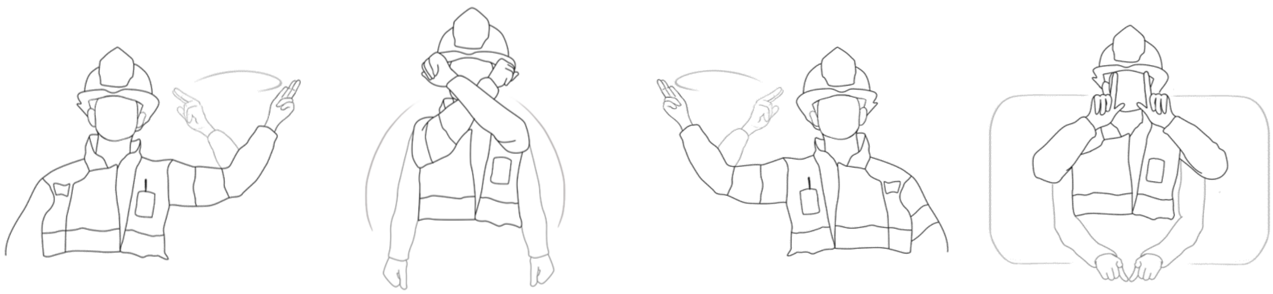
Interestingly, this last scenario would not only require the drone of having the ability to interact with the firefighters, but also require a way to interact with civilians who may have never seen a drone before. Another interesting aspect is that three out of the four tasks (Mapping, Finding Survivors, Detecting Fires) that were identified in the study have also been found in a very recent survey that was conducted with firefighters [39]. In their work, Roldán-Gómez et al. [39] have been focusing on forest firefighting while we took a broader approach and also investigated indoor firefighting scenarios. The final drone tasks are summarized in Table 2.

Gestures for Drone Interaction. The final gestures chosen for each task are illustrated in Figure 5. The questionnaires revealed that participants understood what they were asked to do (μ = 6.8, SD = 0.37) and felt comfortable expressing their ideas and suggestions (μ = 6.6, SD = 0.47). The task agreement ratings revealed a high overall agreement (μ = 6.3, SD = 0.64). The task difficulty ratings revealed low difficulty (μ = 1.8, SD = 0.93). Identifying Hazardous Materials such as gas and chemical leaks was the hardest task for the participant to create a gesture for (μ = 4.2).

Detecting fire gesture includes lifting the left hand and rotating it clockwise, with two fingers up. Finding survivors is equivalent to the Detecting Fire gesture but using the right hand instead of the left one. Identifying hazardous materials includes raising two hands and crossing them in front of the face. Finally, the Mapping gesture consists of creating a "frame" in front of the body using both hands symmetrically with two fingers pointing up. Our participants chose

Table 2: Drone tasks used as referents for the elicitation study. The chosen gestures are presented in Figure 5.

Task	Description	Chosen Gesture
Detecting Fire	Detect number and location of fire spots	(a)
Identifying Hazardous Materials	Identify source and size of gas or chemicals leak	(b)
Finding Survivors	Search for trapped citizens or people in danger and get information on their number and location	(c)
Mapping	Create a map of the floor or building based on exploration	(d)



(a) Detecting Fire **(b) Identifying Hazardous Materials** **(c) Finding Survivors** **(d) Mapping**

Figure 5: Chosen gestures: (a) Detect fire spots (number and location), (b) identification of gas/chemicals leak source and size, (c) search for trapped citizens or people in danger and get information on their number and location, (d) map the floor or building.

gestures that are continuous and repeated, meaning that they will be performed until the desired command is detected, when they receive feedback that the gesture was properly understood.

Interaction Considerations. We here present the additional considerations related to interaction techniques that were raised throughout the study. First, we noticed that two of the chosen gestures are one-handed gestures and the other two are two-handed. When the participants were asked about their physical constraints, they mentioned having to often hold equipment. Still, they chose to design two gestures that require both hands. When we reminded them of the constraints mentioned earlier in the day, they responded that *"one of the team members can do the gesture, while the other is holding the equipment"*. This shows how natural teamwork is to their practices and that they would consider a team-to-drone instead of a person-to-drone interaction. They further mentioned technical considerations, although these were not mentioned by our research team. For example, *"the gesture has to be noticeable by the drone, you can't do a small movement otherwise it won't be seen"*. Indeed, in-situ visibility may be poor, the workload intense, and small gestures might go unnoticed. This example demonstrates that our methodology where one firefighter was wearing equipment and all gestures were discussed as if in context, functioned and that firefighters kept in mind the harsh environments they work in. Participants further discussed the importance of the position of the drone respective to team members. They demonstrated how when exploring a new floor, the drone could follow them and could take the lead upon entering a new room. Regarding feedback strategies, participants proposed that a drone could combine visual and audio modalities. For example, to mark the location of trapped survivors, the drone could make noise or use flickering lights above their location. They furthermore proposed that the drone could display a green light to indicate that it did not find trapped people and a red one in the opposite case.

These two studies shed light on the complexities of drone integration in firefighting and highlighted the opportunities offered by drone technology in supporting emergency responders in their missions. The next section further discusses the results.

5 DISCUSSION

We here present three socio-technical factors of importance when integrating drones in firefighting teams.

5.1 Choice of Gestures for Harsh Environments

Our exploration towards collocated HDI in firefighting led us to choose gestural interaction as the best-suited mechanism to introduce drones in firefighting teams, despite environmental constraints.

We proposed a user-centered approach using interviews, a focus group, and a gesture elicitation study with professional firefighters to fully understand the advantages and limitations encountered by these domain experts in their work. Based on the physical load of the equipment that firefighters carry, we expected the resulting gestures to be one-handed, small, and fast, saving them from additional physical and cognitive efforts to communicate with the drone. However, our study revealed that, regardless of the constraints, the firefighters preferred large, noticeable, and continuous gestures, some of them even two-handed. However surprising, these gestures – continuous and involving large parts of the body, as well as two-handed gestures – are consistent with the gestures used in first-response and military environments [5] for human-human communication. Firefighters are indeed used to communicate with each other by performing gestures that are highly noticeable even in low visibility environments (e.g., smoky or dark settings). These findings are of particular importance for future work looking at implementing gestural interaction with robots in harsh environments. Another finding was that the firefighters preferred high-level commands, considering that the drone would have a high level of intelligence, such as knowing how to position itself or detect complex situations. As such, the firefighters imagined that the drone would work with them as a team member, and as such interact with them using similar gesture types, and additionally either follow them or go ahead depending on the real-time context.

5.2 Drones in Firefighting: Tool or Teammate?

Our national fire and rescue authority has recently started integrating drones in their missions. Our research on how autonomous drones will be able to support them in the future was met with excitement and enthusiasm, both from R&D officers and operational firefighters. This enthusiasm was also found in recent work where Roldán-Gómez et al. [39] conducted a survey with firefighters who expressed a positive opinion about the potential of drones for assisting them in their work. This shows a great leap forward compared to prior research conducted only 4 years ago in Germany where only 15% of the firefighters interviewed saw relevance in the use of drones in their role [42]. This difference in perception between the two prior works might be a result of the technological advances, the growing presence of drones in our societies, and also potentially due to cultural differences.

In our study, participants proposed many scenarios and tasks for drone usage, such as finding information about a fire or civilians on site and reporting the information to the team. Future drones need to be carefully integrated into these complex environments with considerations such as the safety of the firefighters and civilians, the mental and physical workload of operating the drone, how much trust firefighters can put into this technology, and the complexities of the organizational environment [41]. Our work investigated gestural interaction for drones in firefighting and highlighted the need to simplify current work practices, which we propose can be done by providing direct interaction in collocated settings. However, the type of interaction metaphor will be a major component of how drones should be integrated. For example, should the drone be used as one of many tools or be considered as a teammate to the firefighters? In our studies, we found that firefighters envisioned communicating with the drone as they do with each other, using continuous signaling gestures until the other person (or drone) provides feedback that the information is received. Interestingly, recent work in Search And Rescue (SAR) showed that it is possible to include virtual drones to be felt as members of the team [15]. These findings strengthen our vision of future drones that could support firefighting teams in their missions, providing added situational awareness and real-time feedback, potentially becoming a full member of the operational team. Yet, additional research is needed to fully understand the impact of drone usage in firefighting teams.

5.3 Drones for Increased Situational Awareness (SA)

One of the main findings from the two user studies with firefighters is that drones have the potential to increase their SA. Although the need for situational awareness is well documented in the emergency response literature [44], much research is still needed to fully understand how drones can provide such information in a relevant, timely, and non-disturbing manner. Currently, firefighters use real-time data gathered by drones – photos, videos – to gain a better understanding of the situation at hand. However, as we learned in the user studies, processing the raw information that is received by the drone during a mission is a complex task. Firefighters highlighted that they would prefer to receive directly processed information instead, to reduce their workload. In this work, we proposed a novel concept that envisions the drone as part of the operational firefighting team. The scenarios of use identified in the focus group correspond to drone tasks that would improve SA based on the firefighters' needs. We propose that the information gathered by the drone could be given to the firefighters already processed. For example, as technology already enables the detection of fire [48], a processed output of "detecting fire" could include the number of fire spots, their size, and location. This type of output strategy would indeed fully enable drones to increase firefighters' situational awareness.

6 LIMITATIONS AND FUTURE WORK

This work investigated factors towards the future integration of collocated drones in firefighting teams. The work presented in this paper focused on acceptability and input (see Figure 3), but did not investigate feedback strategies. In addition, this work is a first step towards a future of drones integrated into firefighting teams. However, given current technological limitations, we did not have the opportunity, at this stage, to evaluate the influence of autonomous drones interacting with firefighters during an actual mission. Further research is therefore needed to enable the vision presented in this paper including considering various input and output modalities (Figure 6).

In addition to the input and output channels, research is needed to understand how drones and firefighters can work closely together as a team. For example, the notion of proxemics needs to be further researched for conditions where the firefighters are constantly on the move and in action, compared to current research which focused on still participants [52, 55]. Future research could explore additional modalities, such as voice and follow a similar methodology to elicit appropriate voice commands, and then compare advantages and drawbacks of the different input modalities.

While this was out of the scope of this project, we propose that, in the future, once appropriate technologies are developed, the collocated interaction between firefighters and drones should be tested in real-world conditions. We further suggest that empirical user studies should be conducted to investigate how the presence of the drone influences the firefighting mission execution.

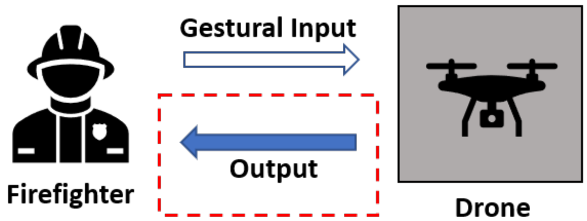


Figure 6: This diagram describes the two main information channels in the collocated interaction between a firefighter and a drone. Future research is needed to investigate appropriate output strategies.

7 CONCLUSIONS

This project investigated collocated human-drone interaction for firefighters who operate in a uniquely complex and constrained environment. We took a holistic approach and worked with the top three domain experts in the country to understand their current usage and future plans for drones. To further understand the applicability of drones in firefighting teams, we ran a focus group and gesture elicitation study with operational firefighters (N=9) at the fire station. Our work was met with much enthusiasm and firefighters were excited to envision a future where drone technologies can support them and help reduce the risks they face in their missions. The studies led to a set of drone tasks and matching gestures for collocated interaction between firefighters and drones. The results from both studies shed light on the firefighters' needs and their approach to future interactions with drones and robots more generally. We finally discuss socio-technical factors which should be considered in future research considering the integration of drones in emergency response. This work contributes new insights into the integration of semi-autonomous drones in the firefighting context.

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