Collocated Human-Drone Interaction: Methodology and Approach Strategy

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***Abstract*—The consumer drone market has shown a constant growth for the past few years. As drones become increasingly autonomous and used for a growing number of applications, it is crucial to establish parameters for collocated human-drone interaction. Prior research showed how ground robots should approach a person to initiate interaction. This paper builds upon prior work and investigates how a flying robot should approach a person. Because of the flight capability, drones present more approach parameters than ground robots and require further study to properly design future interactions. Since research methodologies in aerial robotics are not well established, we present a taxonomy of methodologies for human-drone interaction studies to guide future researchers in the field. This paper then contributes a user study (N=24) investigating proximity, speed, direction, and trajectory towards a comfortable drone approach. We present our study results and design guidelines for the safe approach of a drone in a collocated indoor environment.**

***Index Terms*—human-drone interaction, human-robot interaction, social robotics, proxemics, methodology survey.**

I. Introduction

The last years have seen the emergence of drones, or Unmanned Aerial Vehicles (UAVs), in our day to day environments. First used for entertainment, such as for photography and filming, they are now used for a wide range of applications including delivery, surveying, farming, and search-and-rescue.

Initially, remote controlled by an operator, drones are increasingly becoming autonomous and we expect that in the future all drones will be either semi- or fully automated. As these flying machines become more prevalent, it is crucial to understand how they best fit in our environments and how they should interact with people around them.

For example, we envision a delivery drone would approach a person to deliver a package or to ask them for more information on where to deliver it. In search-and-rescue, drones are currently used to support teams in exploring large areas, understanding terrain, and finding people [1]. In the future, the drone itself could be used to assess somebody's physical and mental states, in which case, it will need to approach the person and initiate interaction, in a non-threatening manner and providing a clear intention to help. While prior research in Human-Drone Interaction (HDI) concentrated on control mechanisms and interaction techniques for drone users (such as [2], [3]), we propose to focus this research work on scenarios where an autonomous drone initiates interaction and in particular how a drone should approach a person, shifting away from the user control paradigm.

Prior work in ground robotics investigated approach strategies for Human-Robot Interaction (HRI) [4], [5]. However, prior work in HDI has shown that HRI findings do not directly apply to aerial robots [2], [6]. Moreover, the additional degree of freedom generated from flying increases the number of approach parameters. Some prior work investigated the height of approach without finding significant differences [7]. To this day, there are no clear parameters of how an autonomous drone should approach a person, which led to the investigation in this research paper.

Since HDI is a recent research area, we find that there are no established methodology or best practice for conducting user studies in the field. As such, in order to run the user study on the best approach strategy, we surveyed existing methodologies for HDI research. This paper presents the taxonomy for HDI user studies which surveys the different methodologies from the human-drone interaction literature, as well as a user study (N=24) investigating specific sets of parameters in proximity, speed, direction, and trajectory towards a comfortable drone approach. The contributions are as follow:

- A taxonomy of human-drone interaction research methodologies.
- A user study (N=24) investigating comfortable drone approach strategies.
- Design guidelines for the comfortable approach of a drone.

The next section reviews prior work and introduces a taxonomy of collocated HDI research methodologies. In the following sections, we describe the study design, results, and discuss our findings for the design of HDI.

II. Related Work

This section presents prior research on interaction distances in Human-Robot Interaction, how robots should approach people, and human-drone interaction.

A. Proxemics in Human-Robot Interaction

The concept of interaction distances was introduced by Hall [8] as "proxemics" for people to people communication. Hall showed that the distance people keep from each other is divided into 4 zones: Intimate, from direct contact to 1.5 feet (0 - 0.5m); Personal, from 1.5 to 4 feet (0.5 - 1.5m); Social, from 4 to 12 feet (1.5 - 3m); and Public, beyond 12 feet (3m).

Prior research investigated proxemics for human-robot interaction, such as Takayama and Pantofaru [9] who found that robots that are directly looking at a person's face influence proxemics' behavior. Mumm and Mutlu [10] found that people tend to maintain further distance with a ground robot when it enters mutual "gaze" with them. Hüttenrauch et al. investigated spatial relationships in HRI [11] and reported that people prefer to interact, and feel most comfortable with a robot in their Personal Space. Walters et al. [12] found in a study that 60% of participants were most comfortable interacting with robots in the Personal and Social space. In their study, approximately 40% of participants got the robot within the Intimate space, indicating their level of comfort.

B. Human-Robot Approach

Walters et al. [4] investigated how a robot should approach a human in a fetch and carry task. In the first trial, each participant was approached by the robot from three directions: front, left, and right. Results showed that people favored an approach from the right-hand side over left and front. Overall, participants were most comfortable with a right-side approach, and most uncomfortable with a front approach. This study also investigated four different conditions with regards to the position of the participant: sitting at a table, sitting in the middle of a room, standing against a wall, and standing in the middle of a room. Results showed that front right and left approaches were rated as the most comfortable across the four conditions, while rear and direct front approaches were the least comfortable.

Butler and Agah [5] analyzed the psychological effects of behavior patterns of a mobile personal robot. Results showed that people were most comfortable with robot approaching at 10 (0.25m/s) and 15 inches/sec (0.38m/s), and the least comfortable with a faster speed of 40 inches/sec (1.02m/s).

C. Human-Drone Interaction

Human-Drone interaction is a sub field of HRI focusing on flying robots. While a large body of work has been focusing on the control mechanism for remote interaction, some recent work on natural collocated interaction [2], [3], [13]. Arroyo et al. [14] showed that the movement and noise created by moving propellers can evoke negative emotions. Monajjemi et al. [15] established a mutual attention between human and an autonomous drone outdoors where the drone acknowledges recognizing a person by hovering and wiggling. Jensen et al. [16] investigated user preferences in human drone acknowledgment. They determined that a high level of acknowledgment can be achieved by combining orientation and salutational gestures in drone flight paths in the preferred distance of 2 meters away from the user.

Recently, Duncan et al. investigated parameters for UAVs comfortable distance, [7] in particular the drone's height when approaching a person. Their results showed no conclusive difference in comfort with a small UAV approaching a person above or below head height. Our research goes further by identifying other criteria of approach, beyond the height of the UAV. Recently, research looked at the design of a social drone [17]. Yeh et al. examined proximity and approach differences between social and nonsocial drones. In their work, the drone was connected to a zip-line system. They found people were comfortable with the drone at a closer distance in its social form. However, a limitation of this work is that the drone is not actually flying or the propellers rotating.

Our paper proposes a systematic evaluation of different parameters for a drone approaching a person in a controlled, yet realistic environment. We use different factors and our research includes both quantitative and qualitative methods. Both types of data add to the literature of human-drone proxemics and give a better understanding of how to design drone interaction in the future. Our paper further contributes to the space of semi- and fully autonomous drones.

III. Human-Drone Interaction Methodologies

Research on interaction with ground robots has been conducted for several decades, yet direct interaction with aerial robots only dates back to the last 5 to 10 years. There are currently no established best practices for running user studies in the field of HDI. As such, a researcher, new to the area, may struggle to decide how to run their user study and to fully comprehend what they will gain from choosing a methodology over another.

We show in this section that different types of methodologies have been used for evaluating HDI, including in-situ studies with drones, studies using Virtual and Augmented Environments, interviews, and remote studies, each with their own advantages and limitations. We find that some studies even combine several methodologies for different stages of the research. We developed a taxonomy to guide future HDI research, presented in (Table I). The taxonomy includes prior research and details existing methodologies, describing them in terms of realism, complexity, safety risks to the user, reproducibility, and scalability.

Realism

There are varying degrees of realism in terms of closeness to a real-life scenario. Methodologies that use a flying drone close to the user present high realism, while an interview may require the participant to imagine a situation or context. Virtual environments offer the option for high realism where a drones movements, noise, and wind generated by the propellers could be accurately represented in a safe environment. However, current VR studies and most available hardware do not offer full sensory experience and as such rank medium in realism.

Complexity

Making a drone fully autonomous for a user study is, to this day, technically challenging. Moreover, flying a drone is subject to local regulations by the civil aviation authority. These lead to high complexity when running the study over sending an online survey for example.

TABLE I: Taxonomy of Human-Drone Interaction Research Methodologies Classified by Order of Realism.

Methodology	Description	Realism	Complexity	Safety Risk	Reproducibility	Scalability
Collocated Flight	**Outdoors.** Drone flying collocated with the participant [2], [15], [18]–[27].	High	High	High	Low	Low
	Indoors. Drone flying collocated with the participant [13], [16], [22], [24], [28]–[32], [32]–[37].	High	Medium to High	Medium	Medium	Low
Virtual and Augmented Reality	Participants interact with a drone in a virtual world or via a virtual or augmented environment [38]–[40].	Medium	Medium	Low	High	Low
Non-collocated Flight	The drone is flying next to the participant but with a separation between them [3].	Medium	Medium to High	Low	Low to Medium	Low
Mimic Flight	Drone mimicking a flying condition [7], [17].	Low to Medium	Medium	Low	Medium	Low
Animations and Videos	Participants watch videos or animations of a drone, either on its own or interacting with someone [13], [41], [42].	Low	Low	None	High	High
Online Survey	Participants answer an online survey [43].	None	Low	None	High	High
Interview	Participants answer questions about interacting with a drone without seeing a drone [2], [7], [18]–[21], [25], [29], [35], [44].	None	Low	None	Medium	Medium

Safety Risk

Drones often present safety concerns to participants. We find that by wanting to increase safety, such as by adding a glass panel between the drone and a participant [3], the study methodology changes compared to when a drone is collocated with the participant [2]. Similarly, a study design can influence the participants behavior, such as when participants are instructed to move out of the way in case of malfunction [35]. Other notions of safety depend on the provided interaction. For instance, some work let the participant touch a drone for VR feedback, with low risk when the drone is fully encased [45], or high risk when the drone is exposed [46].

Reproducibility

When running in-situ studies, the drones trajectory might be affected by elements such as the wind or an indoor air flow. Some prior work preferred mimicking the flight path for higher reproducibility, such as mounting the drone on a platform attached to the ceiling [7] or on a rail [17]. Studies using virtual environments, videos, animations, and surveys are highly reproducible.

Scalability

In-person studies have low scalability compare to online surveys, for example, where a high number of participants can run the study at the same time.

For our research on approach strategy, we wanted for a methodology presenting high realism and reproducibility. The collocated indoor flight methodology was the best suited. When looking at the closest prior research work investigating the influence of the height of a drone approaching a user, the chosen methodology was *Mimic Flight* [7], [17]. However, Jensen et al.'s study on drone acknowledgment [6] used *Indoor Collocated Flight*, which is the best fit according to the taxonomy. This methodology presents higher realism but is has higher complexity and risk associated to running it.

IV. User Study for Drone Approach

This section presents the study design and procedure for determining comfortable drone approach parameters. We hypothesize that different approach parameters will influence the participants' comfort level and that the results from the study will differ from prior work with ground robots.

A. Participants

Twenty four participants were recruited from within local academic institutions (12 male, 12 female), from 19 to 56 years old (μ = 26.2, SD = 7.2). The order of the conditions was counterbalanced using a Latin square design. Participants were students and academic staff with a background in business, psychology, computer science, and communications. The user study lasted approximately 45 minutes and all the participants were compensated 30NIS (US$10 in local currency) for their time. Most participants (21) had seen a drone before, 8 had piloted one, and one of the participants owed one.

B. Setting and Apparatus

The study was run indoors in a large open space (17x9x5m). Participants were asked to stand on a line and watch the drone as it would approach them. The experiment was conducted in a controlled environment, including controlling the ventilation system in the room, checking that the battery level of the drone was always above a threshold, and verifying the initial positioning of the drone before each take-off. The study was run with a Parrot AR.Drone 2.0 fitted with an indoor safety hull (58x13x58 cm) which was programmed to fly autonomously along a set of pre-defined paths.

TABLE II: Summary of the 12 study conditions and corresponding approach parameters.

Proximity	Speed	Direction	Trajectory
Intimate - 0.5m	Slow - 0.25m/s	Front	Straight
Personal - 1.2m	Moderate - 0.5m/s	Front-right	Up-to-down
Social - 2.4m	Fast - 1.0m/s	Rear	Down-to-up

C. Approach Parameters

As presented in II. Related Work, prior research investigated several parameters affecting users' comfort when a drone or a robot approaches a person.

Proximity: In two research papers, interaction with robots was once shown to be most comfortable within a person's Personal space [11] and once in the Social space [12]. They showed that some participants were even comfortable within the Intimate space [12]. As such, we propose to investigate the differences between the three proxemics zones: Intimate, Personal, and Social.

Speed: Prior work showed the influence of a robot's approach speed on users' comfort [5]. People were most comfortable with the ground robot approaching at a speed of 0.25m/s and 0.38m/s and least comfortable with a faster speed of 1.02m/s. We chose to investigate three different speeds for drones: Slow (0.25m/s), Fast (1m/s), or Moderate (0.5m/s) as the intermediate speed between the slow and fast conditions.

Direction: Prior work showed that participants favored a ground robot approaching from the right-hand side over the left and front [47]. In another study, overall the right and left approaches were rated as the most comfortable, while rear and front approaches were the least comfortable [4]. We propose to investigate three directions: Front, as it is the current way drones approach people in the literature; Front-right as it should be the most comfortable approach strategy if the research in ground robots applies to drones; and Rear, as when the drone would arrive from behind the person.

Trajectory: Drones have an additional dimension in space over ground robots. As such, we decided to investigate three different trajectories for the drone to approach a person: Straight, Up-to-down, Down-to-up.

Prior research could not prove that the height of a drone approaching a person influenced the size of personal space or comfort level [7]. As such, we fixed the drone's flying height.

D. Conditions & Implementation

We investigated three conditions per approach parameter. While 81 combinations are possible, the study uses a 4x3 design where only one parameter is being varied at a time and other parameters are set to a neutral value. The twelve conditions are summarized in Table II.

In terms of implementation, the drone's starting position is on the ground and positioned 8.2m away from the participant. The drone follows a pre-defined path that changes based on which parameter is being tested. By default, the drone flies along the following pre-defined path: it takes off until it reaches its neutral flying height of 1.75m, flies in a straight line towards the participants at the moderate speed, and stops in the personal space. Upon reaching the participant, the drone hovers at the neutral height for 5s and turns around to land. The pre-defined path is modified as follow for each parameter:

Proximity: The drone's final distance to the user is within the Intimate, Personal, or Social space.

Speed: The flying speed is either Slow, Moderate, or Fast.

Direction: The Front approach corresponds to the default path described above. In Front-right, the drone's start position is moved to the right. After flying 5.5m horizontally from take off, the drone turns 45°clockwise and continues towards the participant. In Rear, the flight path is not modified, instead the participant stands with their back to the drone at a distance of 3m from the drone's starting position. The drone's flying height is raised to 3m.

Trajectory: Straight corresponds to the default path described above. In Up-to-down, the drone starts flying towards the participants while going up till it reaches 3m. Once the drone has reached the participant, it lowers itself to the neutral height. In Down-to-up, the drone takes off until it reaches 3m height, it then flies while lowering itself to 0.3m. Upon reaching the participant, the drone rises to the neutral height.

Prior to the main study, we conducted a pilot (N=7) to verify the experimental setup. This pilot study allowed us to finalize the implementation and better control the environment. The following section details the study procedure.

E. Procedure

After welcoming the participant, each session started with signing the consent form and a short introduction to the study. Participants were asked to observe the drone's movements and to fill in a short survey after each trial. There were a total of 12 trials, one per condition and each session took approximately 45 minutes.

The Self Assessment Manikin (SAM) test [48] was used to assess participants' emotional state before, during, and after the study. The SAM test is a 9-point Likert scale using sketches of a manikin to measure emotions along three dimensions: Valence, Arousal and Dominance. Choosing between pictures instead of using words helps people express feelings that could be difficult to externalize. *Valence* relates to the hedonic tone and varies from negative to positive emotions (e.g., frustration *vs* pleasantness); *Arousal* relates to bodily and mental activation and varies from calm to excited (e.g., satisfaction *vs* happiness); *Dominance* relates to the degree of control, between being submissive or in control (e.g., afraid *vs* angry).

In addition to the SAM test, the survey given after each trial was comprised 3 questions on a 5-points Likert scale: how they judged the speed of the drone (from 1: too slow to 5: too fast); how comfortable they felt (from 1: not at all to 5: extremely); how they judged the distance between them and the drone (from 1: too close to 5: too far).

After each parameter was tested, participants had to sort the three conditions they observed for this parameter by order of preference. A Latin square was used to counterbalance

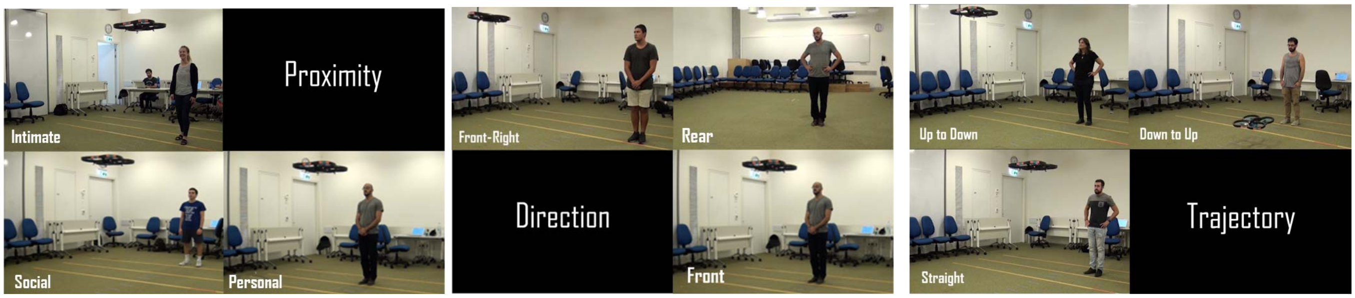

Fig. 1: Examples of conditions tested during the experiment. From left to right: Proximity (Intimate, Personal, Social), Direction (Front, Front-right, Rear), Trajectory (Straight, Up-to-down, Down-to-up). Not represented: Speed (Slow, Moderate, Fast). The twelve conditions are summarized and detailed in Table II.

the order of the trials. After completing the 12 trials, participants filled in a demographic questionnaire. A 15-minute semi-structured interview concluded the study. The interview covered the participants' feelings towards drones and their impression of the study. Participants were asked about current and future applications, acceptable control mechanisms, preferred interaction modalities, as well as perceived safety. The interview was audio and video recorded.

V. RESULTS

The following section describes the data analysis and the results of the participants' preferred conditions, SAM test, surveys, and post-study interview.

A. Preferred Conditions

The mean rank, or rank central tendency [49], for each condition is presented in Table III. A lower value means that the condition was preferred by participants. We performed a Friedman test to compare how conditions were ranked, and post-hoc analysis with a pairwise Wilcoxon signed-rank tests, corrected for multiple comparisons using false discovery. We found that most of the conditions significantly differed within each category ($p < 0.01$). In terms of preference, for each parameter, we found that:

Proximity:

- Personal was significantly preferred over Intimate and Social.

Speed:

- Moderate was significantly preferred over Slow and Fast.

Direction:

- Front was significantly preferred over Front-right and Rear.

Trajectory:

- Straight was significantly preferred over Up-to-down and Down-to-up.

TABLE III: Mean ranks of conditions. The preferred conditions are highlighted in blue. (**: significant difference across conditions with $p < 0.01$).

Condition		Mean Rank
Proximity	Intimate	2.71**
	Personal	1.29**
	Social	2**
Speed	Slow	2.33
	Moderate	1.21**
	Fast	2.46
Direction	Front	1.13**
	Front-right	1.92**
	Rear	2.96**
Trajectory	Straight	1.46**
	Up-to-down	2.21
	Down-to-up	2.33

B. SAM and Survey

Overall, during the experiment, the mean arousal as measured by the SAM test was 5.08 (SD: 1.60), the mean valence 6.75 (SD: 1.20), and the mean dominance 6.02 (SD: 1.73). From the other questions, the mean perceived speed was 2.81 (SD: 0.67), the mean comfort 3.35 (SD: 0.80), and the mean perceived distance 2.82 (SD: 0.64).

To analyze the effect of conditions on the participants' emotional responses, we analyzed the survey given after each trial with a Markov Chain Monte Carlo (MCMC) method [50]. MCMC is a Bayesian statistical method that can accommodate multiple variables at once instead of artificially increasing the number of tests. MCMC works by incrementally estimating responses' distribution parameters. While powerful, this method is computationally taxing. The model used in MCMC included SAM emotional dimensions as a response (dependent variables) and the experimental conditions as fixed effects (independent variables). The 4×3 design was accounted for and all comparisons were made using balanced data. Due to the stochastic nature of MCMC, we controlled for the results convergence by using Gelman and Rubin's Convergence Diag-

TABLE IV: Effects of each condition onto the participants' emotional response and overall perception. The overall mean are compared to the groups' means and shown with the 95% CI. (* $p < 0.5$, ** $p < 0.01$, – no statistical significance). Increased means are highlighted in blue, while decreased means are highlighted in yellow.

Conditions		SAM			Comfort	Perceived	Perceived
		Valence	Arousal	Dominance		Speed	Distance
Mean		6.75	5.42	5.71	3.50	2.79	2.63
Proximity	Intimate	–	–	–	-0.54** [-0.93;-0.16]	–	-0.42** [-0.71;-0.12]
	Personal	–	-0.50* [-1.00;0.00]	+0.54* [0.06;1.02]	–	–	+0.33* [0.04;0.63]
	Social	–	-0.71** [-1.20;-0.21]	+0.96** [0.48;1.43]	–	–	+0.62** [0.32;0.91]
Speed	Slow	–	-1.04** [-1.54;-0.54]	+1.17** [0.69;1.64]	–	-1.25** [-1.49;-1.01]	+0.67** [0.37;0.96]
	Moderate	–	–	+0.67** [0.20;1.15]	–	–	–
	Fast	–	+0.63* [0.13;1.11]	–	-0.54** [-0.92;-0.16]	+1.04** [0.81;1.28]	–
Direction	Front	–	-0.92** [-1.42;-0.41]	+0.83** [0.36;1.32]	–	–	+0.33* [0.04;0.63]
	Front-right	–	-0.54* [-1.04;-0.05]	–	–	–	–
	Rear	–	+0.62* [0.13;1.12]	-0.67** [-1.15;-0.20]	-0.87** [-1.24;-0.48]	–	–
Trajectory	Straight	–	-0.75** [-1.24;-0.25]	–	–	–	–
	Up-to-down	–	–	–	–	–	–
	Down-to-up	–	-0.63* [-1.12;-0.12]	–	–	–	+0.37* [0.08;0.67]

nostic [51] on 10 chains. The resulting multivariate potential scale reduction factor (MPSRF) was 1.003. The significant differences found are summarized below and presented in Table IV along with the 95% confidence intervals.

Proximity:

- Intimate: decreased comfort and perceived distance.
- Personal: increased dominance and perceived distance, decreased arousal.
- Social: increased dominance and perceived distance, decreased arousal.

Speed:

- Slow: increased dominance and perceived distance, decreased arousal and perceived speed.
- Moderate: no significant difference.
- Fast: increased arousal and perceived speed, decreased comfort.

Direction:

- Front: increased dominance and perceived distance, decreased arousal.
- Front-right: decreased arousal.
- Rear: increased arousal, decreased dominance and comfort.

Trajectory:

- Straight: decreased arousal.
- Down-to-up: increased perceived distance, decreased arousal.
- Up-to-down: no significant difference.

We compared the differences between genders using MCMC analysis; overall, across all conditions, we did not find significant differences between how male and female participants answered the different scales. Finally, we used Wilcoxon tests adjusted for multiple comparisons with the false discovery rate to compare the results of the SAM test before and after the experiment and did not find significant differences in the dimensions of emotions.

C. Interview Results

The following items present the qualitative data gathered from the post-study interview around four themes.

Control and Autonomy

All but two participants understood that the drone was not remote controlled, and half of them specifically mentioned it as autonomous or pre-programmed. Most (64%) thought that the drone was aware of them, as P10: *"it was aware of the fact that I was there not to crash on me"*.

Approach

When asked at the end of the study about the ideal approach parameters, fifteen participants answered that they would prefer the drone to come straight towards them, others would prefer a side approach, and overall 72% stated that they did not feel comfortable with the drone approaching from the rear. Fifteen participants preferred the approach at eye level, seven mentioned that it should be from above, and a few mentioned that the drone should stop at chest level to provide them with more control. Four people stressed the importance of the drone not crossing onto the Intimate space.

Anthropomorphism and Zoomorphism

Most participants discussed the drone as they would describe people, animals, or insects: *"his sound and the movement reminded me [of] a huge bug"* (P4), it is *"like with a pet, not like a toy, the toy is something you throw away, and I would never throw him [drone] away"* (P2). Several participants assigned facial features such as eyes to the drone. Participants gave it gender and attributed it with human behaviors, such as: *"When he approached me he kept a [...] distance"* (P10); *The drone "looked at me and seemed like he was taking a video of me"* (P16). One participant compared the drone to a kid and addressed it directly *"No, don't go..."* (P6).

Drone Intent

Most participants (64%) interpreted the drone movement as the drone intending to communicate with them. They mentioned this was due to the direction of approach, as in the Front condition, or the position of the drone itself (Proximity): *"He came to me for something. Maybe just to say hi"* (P17). We find that participants interpreted the drone's behavior as intent, such as P15: *"When it hovered I thought it wanted something from me"* or P2 who referred to the drone as *"looking directly at me"*. One person specified that the drone's aim was *"to identify me, because he stayed for a couple seconds and then left"* (P12).

"It was funny to see how I felt when the drone was close to me. It was a weird feeling. I wouldn't want it to be closer"	P4
"It was the first time I saw a drone so I enjoyed just seeing one. It was friendlier than I thought a drone would be like"	P14

Drone Perception

When asked about their perception of drones after the study, some mentioned that they were surprised how accurate the drone can be, however the technology is noisier than they expected. Four mentioned that after participating in the experiment they were thinking about buying their own drone. Some of the positive usages of drones were mentioned such as in search-and-rescue or delivery. However, a few participants mentioned issues around privacy, safety, and military usage: *"it can injure someone if it hits them or if someone reaches out to touch it"* (P16). Some discussed a change in perception *"in my mind drones were a military thing but I think this perspective is changing, now people use it for fun"* (P11). Thirteen people mentioned that the experiment was an exciting experience.

VI. Discussion

This section discusses the results of the user study.

A. Comparison of Comfortable Approach Parameters Between Ground and Flying Robots

One major goal of this work was to identify how a drone should approach a person and describe how this differs from the literature on ground robotics. For the following parameters, we only discuss significant differences:

Proximity

The Personal distance (1.2m) was preferred overall, which is in par with prior work with ground robots [11], and even closer than in [12]. When the drone was in the Intimate space, comfort decreased, but it did not increase with added distance. When the drone was further away, arousal decreased and dominance increased, meaning that participants felt more calm and in control.

Speed

The Moderate speed (0.5m/s) was the most comfortable, over a slower and a faster speed that were respectively considered too slow or too fast. We find that the Slow speed decreased arousal, while the Fast speed increased it. Participants felt a higher dominance, more control, as the speed decreased. We also find that the Fast speed reduced comfort. Prior work on ground robots showed that people were most comfortable with robot approaching at a speed varying between 0.25 to 0.38m/s [5]. We find that the drone's comfortable speed is faster than with a ground robot, which is in par with prior work by Duncan et al. [40] using *Virtual Reality* and showing that an increase in the drone's speed increases preference. We note that the optimal speed in-situ is slower than in the virtual environment.

Direction

The Front direction was preferred overall. Our results differ from prior work with ground robots [4] as Front was rated with a higher dominance than Front-right. The Rear approached decreased comfort and dominance. Participants were more anxious when they could not see the drone approaching and were sometimes surprised when feeling the propellers' blow from behind them.

Trajectory

The Straight trajectory is preferred over the Up-to-Down and Down-to-Up approaches. Trajectory did not seem to affect participants beyond arousal which was the lowest in the Straight condition, meaning the participant felt calmer.

B. Safety and Control

Most participants (85%) mentioned feeling completely safe despite not feeling in control of the drone. In our study, the propellers were enclosed inside a protective hull, which could have increased the participants' sense of safety. Some mentioned feeling in control *"because I could stop it with my hands. If it would come too close, I would push it back"* (P12). We anticipate that a different drone form factor might lead to different results and worry that people would be willing to touch a drone, or push it, even when the propellers are not protected, leading to unsafe behaviors.

C. Gender Differences

Overall the ratings were similar between female and male participants. Yet, we observed trends when we refined our analysis. In some cases, the observed differences across all participants could be due to a stronger reaction from one gender. For example, only male participants had a higher arousal and a lower dominance when the drone was approaching from the rear. While our current number of participants does not enable to draw conclusions, the fact that some groups might not be as sensitive as others to specific characteristics of a drone approach constitutes an interesting research direction. Besides understanding the causes of such discrepancies, designers of human-drone interaction might want to determine the most salient parameters in their future work.

VII. Limitations

The indoor study setting might have led participants to feel safer than in an outdoors study. We also expect their reactions to differ in an uncontrolled environment where a drone approaches them without prior notice. From a technical perspective, the autonomous drone flight reduced our ability to provide real-time position correction and we observed some variability in the path of the drone during the experiment. Future work should consider using an external tracking system or embedded sensors such as camera or inertial measurement unit (IMU) to position the drone according to the user in real time. However, the chosen methodology was more realistic than prior studies.

VIII. Future Work

Future work will include moving the experiment to the outdoors and testing in-the-wild to verify how the environment affects the drone approach parameters. Furthermore, additional parameters should be investigated such as variations in the noise and wind generated by the drone, additional form factors (such as fixed-wing drones compared to quadcopters), drones with and without a protective hull, and with drones of different sizes and appearance.

IX. Conclusions

As drones increasingly become part of our environment, it is crucial to understand how to design them to interact with people. In this paper, we presented a taxonomy of human-drone interaction methodologies and established parameters for an autonomous drone to approach a person. In a user study with 24 participants, we showed that people favor interaction distances within the personal space over the intimate and social proxemics spaces. We found that participants prefer a certain speed over others considered too slow or too fast. Lastly, we found that participants preferred a front approach and disliked the drone flying from the rear. We find that some of these approach parameters differ from prior research with ground robots. Furthermore, while our study focused on drone approach, we found that most participants thought that the drone wanted to communicate with them, proving the importance of the approach parameters. Our work contributed to a set of parameters for comfortable collocated human-drone interaction. We also introduced a taxonomy of methodologies for human-drone interaction studies that we hope will guide future researchers in the field.

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