

Investigation of Human-Robot Comfort with a small Unmanned Aerial Vehicle compared to a Ground Robot*

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Abstract—This paper presents an investigation of human comfort with a small Unmanned Aerial Vehicle (sUAV) through a study offering a comparison of comfort with a sUAV versus a ground vehicle. Current research on human comfort with sUAVs has been limited to a single previous study, which did not include free flight, and while ground vehicle distancing has been studied, it has never been directly compared to a sUAV. The novelty in the approach is the use of a motion capture room to achieve smooth trajectories and precise measurements, while conducting the first free flight study to compare human comfort after interaction with aerial versus ground vehicles (within subjects, N=16). These results will contribute to understanding of social, collaborative, and assistive robots, with implications for general human-robot interactions as they evolve to include aerial vehicles. Based on the reduced stress and distance (36.5cm or 1.2ft) for ground vehicles and increased stress and distance (65.5cm or 2.15ft) for sUAVs, it is recommended that studies be conducted to understand the implications of design features on comfort in interactions with sUAVs and how they differ from those with ground robots.

I. INTRODUCTION

This work will contribute to a fundamental understanding of how humans perceive small Unmanned Aerial Vehicles (sUAVs) in interactions and lay the groundwork for future expanded investigations, while providing baseline information for smarter interaction algorithms. Motivation for this work has been derived from the expected prevalence of sUAVs in public spaces, as well as the prior research in peoples' reactions to these vehicles in public [1], [2].

The specific research question being investigated in this work is: *How does the type of vehicle impact the comfort of people interacting with a robot?* To understand this question we are interested in the distance at which people stop an approaching robot, affect reported by interactants, and qualitative responses of the interactants. Through the investigation of these relationships, it is expected that recommendations will be developed for the application of previous robot findings to aerial vehicles, settings which will increase comfort in interactions, and areas of future work.

This paper introduces claims about the comfort of participants when interacting with a ground vehicle compared to a sUAV, and relates these to the human-human and human-ground robot findings. These claims will form the basis for understanding human-sUAV interactions through the first free-flight distancing investigation of human comfort in aerial vehicle interactions. The novelty of this work is in

comparing different types of robots (ground and aerial) to understand comfort (defined as distance, affective response, and qualitative responses) in collocated interactions. The findings of reduced stress and distance (47.6cm or 1.56ft) for ground vehicles and increased stress and distance (65.1cm or 2.14ft) for sUAVs will be presented along with a testbed for these interactions. Recommendations for future work on comfort in interactions with sUAVs and how they differ from those with ground robots will also be provided within the context of the findings presented here.

II. RELATED WORK

This section will cover related work in human-sUAV interaction, proxemics, and personal space with both human and robot agents in order to situate the current work.

A. Human-sUAV Interaction

Work in collocated human-sUAV interaction has progressed from simple gestural control to conveyance of state information, but to date there has not been any work to understand personal space between humans and free flight sUAVs. The current state-of-the-art with sUAVs has been to communicate high-level state information (such as affective, or emotional, state [3], [4]; intended destination [5]; and intended direction of flight [6]) or to investigate gestural control of a sUAV [7], [8], [9]. Previous work has suggested that naive users seem to have an assumption of product safety and may not distance themselves appropriately [2], [10] when encountering sUAVs, which is exemplified by the news reports from injuries caused by hobbyist uses of sUAVs [11], [12], [13]. While work in sUAV interactions is important, it cannot be fully realized until researchers understand how people perceive and intend to interact with sUAVs because the vehicles will need to be able to respond in an appropriate way in order to maintain safe interactions.

B. Proxemics

Proxemics is a foundational area of work in human-human and human-robot interaction (HRI) which explains the preferred distancing between interactants, was defined by Hall in [14], and is based on Hediger's work on fight or flight boundaries in animal interactions [15]. Hall defines space in terms of visual, auditory, olfactory, thermal, and tactile senses which all contribute to distancing in one of four zones. The intimate (0-0.45m), personal (0.45-1.2m), social (1.2-3.6m), and public (>3.6m) zones are widely used in both human-human and HRI literature to situate findings in terms of this foundational work. In summarizing findings from their

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work on human-ground vehicle distancing, Walters et. al [16] proposed a framework for predicting human-robot distances and noted that individual preferences were suggested to have a large impact on distances (and should be studied further).

While proxemics is a foundational area of interaction, it is broader than this work. For instance, the thermal and olfactory dimensions that are present in human-human interactions are not present in the same way with HRI work. Instead, the authors propose that the personal space studies based on Hall's work, such as [17] or [18], might better allow an understanding of environmental or personal factors.

C. Personal Space

Previous work in human-agent personal space studies will be summarized, and split into: human-human distancing, human-ground robot distancing, and human-sUAV distancing. The work described here primarily uses the stop-distance technique developed by Kinzel in [17] and described with recommendations for use by Hayduk in [19]; this technique requires the subject to stand in place and say "Stop" when "the approacher's closeness began to make them feel uncomfortable"[18].

Personal space in human-human interaction has traditionally focused on the person (or agent) approaching another person, whether seated or standing, and the environment in which the interaction takes place. The works described here are only those of interactants who were standing and approached by an experimenter. Agent factors are the observable features of the approaching agent which may impact an interaction. The major findings for agent factors impact on distancing are: angle of approach increases personal space required by the interactant as the agent moves from the interactant's front to their rear [20], [17], and as the height of agent increases, the interaction distance required also increases [21], [22]. Environmental conditions are those features of the environment that are readily identifiable and can be measured. The major findings of environmental conditions on interaction distance are: reduced lighting increases distance [20], reduced ceiling height increases distance [18], decreased room size increases distance [20], and indoor locations have larger distances than outdoor [23]. Additionally, human-human studies found that distancing is a reflexive response, and human-human distances only decreased by 8% when they were observed as long as approach velocity is limited to around 20 cm/s [19].

Human-ground vehicle distancing has traditionally focused on the robot approaching while ignoring environmental conditions (which can lead to a lack of reproducibility). Without any insights into the environmental conditions encountered, it is difficult to design interactions for agents in real-world environments with differently sized rooms, variable lighting, and inconsistent ceiling heights. Findings for human-ground vehicle distancing based on agent factors include: increased gaze generally results in increased distance [24], [25], people allowed mechanoid robots closer than humanoid robots (might be due to humanoid being taller than the mechanoid) [26], and height of agent affects interaction

(adults prefer taller robots)[27]. Findings based on personal factors include: male participants distance further than female participants [24], pet owners maintain a smaller personal space [25], and personality findings such as extraversion leads to higher tolerance of inappropriate spacing [28] as well as proactive subjects stopping the robot earlier [29]. When considering the experiment design, both Takayama and Pantofaru and Walters et. al have suggestions that are relevant here. Both studies [25], [16] found similar distances whether the human approached the robot or vice versa. Walters et. al found that repeated studies with the same subjects reduced distances by almost a third [30] and a speed of 1 m/s resulted in an overshoot of about 0.5m [29].

As discussed in the human-sUAV interaction section, human-sUAV distancing is a relatively new paradigm and, as such, has been studied by only three sets of researchers, and only studied extensively by Duncan and Murphy. Initial studies were conducted in 2013 on the the appropriate height of operation and noise generated by the sUAV. Duncan and Murphy [10] conducted the first collocated experiment in which an AirRobot AR-100B approached a person to test whether sUAVs conform to the norms established for personal space. The results revealed no difference in preference between sUAV heights. Liew and Yairi [31] considered the effects of noise and appearance on interactions with a blimp and Parrot AR.Drone and suggest that the blimp might be a better social platform. Additionally, while the focus of the study was not proxemics and it was conducted outdoors, Cauchard [9] found that more than a third of their 19 participants let the DJI Phantom 4 within their intimate space ($N = 7$), more within personal space ($N = 9$), and only three preferred to distance in their social space.

D. Human-Robot Design Considerations

The majority of HRI research considers whether robots are treated as social actors, which is largely based on Nass' work on the Computers are Social Actors (CASA) model [32]. Under this model, it is expected that when people interact with computers, they will interact socially and this has been reiterated through investigations in HRI. While several HRI researchers have investigated how robot design impacts the resultant interactions, a sampling of those papers will be discussed here to inform the discussion of possible implications for future studies.

Designs for both expressive and non-anthropomorphic robots (along with their movements) have been investigated for their ability to communicate their abilities. Bartneck et. al [33] investigated the perceived intelligence of mechanoid versus expressive robots in an interaction task and found that more animated robots were perceived as significantly more intelligent. They recommend that animated faces are also more likely to engage human attention. Hoffman and Ju [34] describe design methodologies to allow a robot's design to reflect the communicative ability of non-anthropomorphic robots, but are limited in the different challenges encountered when considering the flight paths of a sUAV rather than body movements of a ground-based system. The challenge of

discovering and implementing the right movements are still present, but the challenge of matching form to movement may be better stated as matching form to safe movement.

Another concern is expressed by Klemmer, Hartman, and Takayama in [35] where they discuss the role of embodiment in interaction design, and specifically in the theme of “risk”. They argue that actions which cannot be undone involve more risk and that this is the most important characteristic of physical (rather than virtual) interactions. Another argument is in the theme of “thick practice” where designers should seek authenticity in interactions rather than simulating the world; this is a concern in the laboratory studies described here and will be discussed further later.

III. HUMAN-ROBOT DISTANCING TESTBED

The experimental setup of Cochran and Urbanczyk [18], which studied the relationship between vertical space and personal space in human-human interactions, was replicated. Some modifications were made to the experiment space due to differences in the layout of the lab space available and the addition of a robotic agent. The modifications consisted of using a movable wall to match the width of the experiment room in [18] and installing Vicon cameras in order to add a motion capture system. The ceiling height of the experiment room in our study was also different than in [18] (2.74m rather than their 2.13 and 3.05m). A schematic diagram of the experiment room is presented in Fig. 1.

Following [18], a room measuring 4.88 by 4.56m with ceiling height of 2.74m was partitioned into two sections using a movable wall of length 4.20m. The enclosed section of the room (4.88 by 3.53m) was used as the experiment space where interaction between participants and robots occurred. The outside section (4.88 by 1.03m) was used as a room to control the robots from the computer, to observe the experiments via live video feed, and to allow the backup human pilot to take control of robots if necessary. Ten Vicon Bonita motion capture cameras for tracking robots and participants, along with two Sony CX440 video cameras for observing and recording experiments were installed in the test room. On the floor of the test room, the starting position of the robots (R), the position of the participant (S), and the center of the experiment space were marked with tape (see Fig. 2). Pictures of the experiment space are presented in Fig. 2 where the Vicon cameras are highlighted by solid yellow rectangles and the video cameras are highlighted inside cyan rectangles with broken borders. Because of the robot setup in the experiment space before the participants, we switched the positions of S and R in our study.

An additional component adapted from Cochran and Urbanczyk was the participant interaction (with a single approach per experimenter, or robot, and interactant) and script, which was modified for use with robots. In interactions with the robots, the following script was read to the participants, the part in brackets was read only prior to sUAV interactions:

“A robot will approach autonomously from the mark near the opposite corner of the room. [It will launch and then come slightly forward with a turn.

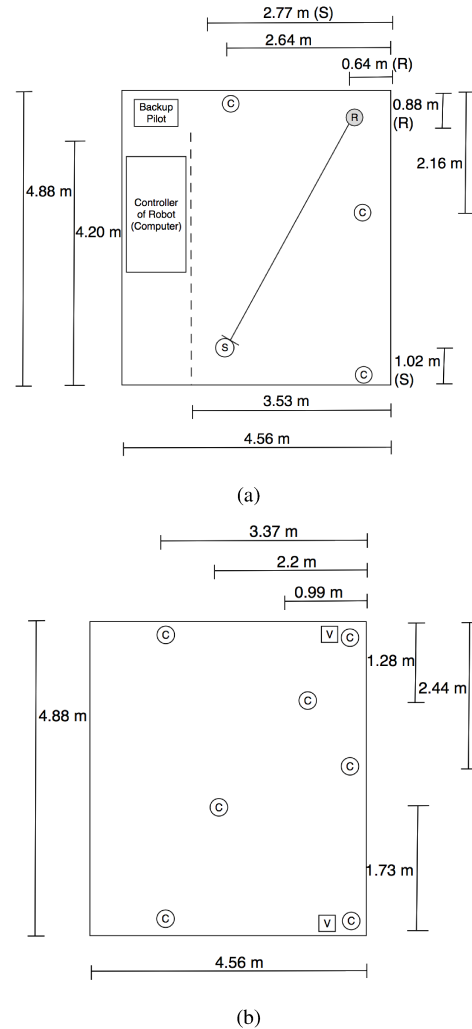


Fig. 1: Diagrammatic top view of experiment room, with top cameras (1a) and bottom cameras (1b). Left and bottom measurements reflect room dimensions and length of the movable versus stationary wall. Top and right measurements reflect distance of Vicon cameras, starting point of the robot (R), and position of subject (S) from the corner.

The robot will then hover and come towards you.] You are requested to stay in place, keep your hands by your side, and say “stop” when the robot’s closeness begins to make you feel uncomfortable. After you say stop, the robot will stop near that position, go back to the center of the room, and park [land].”

IV. HUMAN-GROUND VERSUS HUMAN-sUAV INTERACTIONS

The study was conducted with the goal to directly compare personal space with a ground (telepresence) robot to a sUAV in order to understand whether the findings from ground robots and humans are likely to be directly applicable to aerial vehicle interactions (as would be expected based on the CASA model [32]). This section will describe the robots, hypotheses, study design, participants, and procedures before

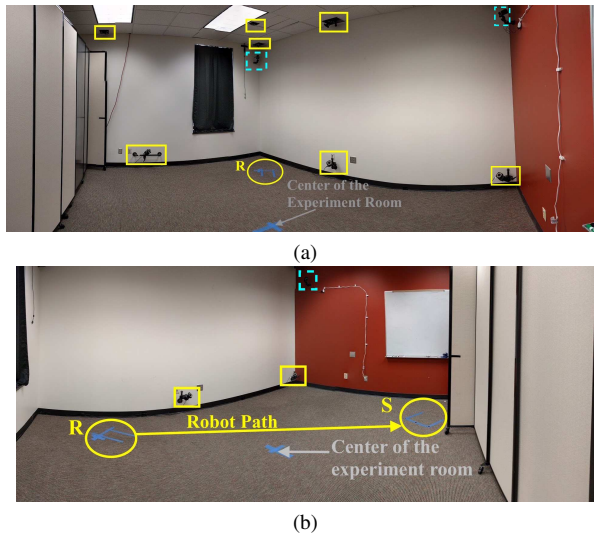


Fig. 2: Experiment room from subject view (2a) and opposite corner (2b). Vicon cameras are shown in solid rectangles, video cameras in broken rectangles, and the starting position of the robot (R) and participant (S) are shown in circles.

presenting the results and discussion of findings.

This was a within-subjects study to examine whether robot type (ground versus aerial) might affect user distancing and affective response to the robot. The independent variable was robot type (ground versus aerial).

A. Hypothesis

The primary hypothesis in this study was that people would display different levels of comfort with the different types of robot. This was assessed through the distance at which they stopped the robot, the difference in affective state reported after interactions, and qualitative reports.

B. Participants

Participants were recruited through emails to campus mailing lists, advertisement monitors around campus, and flyers both on- and off-campus. Sixteen participants (10 male, 6 female) with an age range of 20-62 ($M=30.19$, $SD=12.52$) were involved in this study. Eight participants (one female, seven male) reported prior interactions with remote controlled aircraft, though only five male participants reported owning a system. Participant heights ranged from 1.57 to 1.96m ($M=1.77$ m, $SD=10.2$ cm), with eye heights ranging from 1.44 to 1.91m ($M=1.66$ m, $SD=11.2$ cm).

One important note about the robot experience questions is that they were phrased to solicit interactions in a broad context. Robot experience was assessed by: asking whether participants had “ever interacted with a robot”, the frequency of interaction, and the type of robot (consumer, including Roomba or a pool cleaning robot; industrial, including telepresence or other workplace robots; educational, including Lego Mindstorms or those in a museum; or entertainment, including Parrot AR.drone, DJI Phantom, or Sony Aibo). These prompts also serve to remind people about times when they may have interacted with a robot, so might be overly

sensitive to individual interactions. Within the participants described here, 8 of 16 reported robot experience, while half of those had only interacted with a robot once (two educational, one industrial, and one entertainment).

C. Experimental Materials

The robot systems used in this work were an Ascending Technologies (AscTec) Hummingbird and a Double Telepresence Robot. Both robots were operated with heights (measured to the top of the robot) of 1.52m (5ft). The Hummingbird (Fig. 3a) is a quadrotor weighing 368 grams (0.81lbs) with a diameter of 0.54m (21in) which is widely used for research. The Double (Fig. 3b) is a commercial robot which weighs about 6.8kg (15lbs) and has a remotely adjustable height between 1.19m (47in) and 1.52m (60in). These systems were controlled by a ROS script, in coordination with a Vicon motion capture system to approach the person. In order to control variability as much as possible, robots had marked starting points, the robot paths were scripted, and participants were asked to stand in a designated position. The path of Hummingbird was fully autonomous (in three dimensions) whereas the Double followed a straight line path from its start position (leading to potential variability in angle of approach, which was controlled through aligning with a tape line). The participants, wearing a fiducial marker (Fig. 3c), and robots were both tracked using Vicon. Participants were protected from collision through the use of both a software controller and a backup pilot to take control of the vehicles if needed. Distance from robot to the participant was measured by the Vicon system and will be reported in minimum horizontal distance.

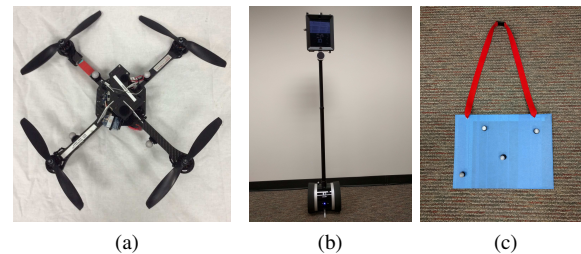


Fig. 3: Materials used for interactions with participants, AscTec Hummingbird (3a), Double Telepresence robot (3b), and Participant Fiducial Marker to track their location (3c).

D. Experimental Procedure

The study took approximately one hour and consisted of four parts: i) pre-interaction, ii) interaction, iii) survey evaluations, and iv) post-interaction.

1) *Pre-Interaction*: The pre-interaction began when participants were greeted and provided consent forms with information about the study objective (to assess the impact of the design of a robot and the height of its operation on the personal space requirements of the general population) and their rights as a participant. After signing the consent forms, participants were provided with a pre-questionnaire to collect data about their general background, familiarity with robots, sociability and stress level before interacting with the robots. After filling out the questionnaire, handedness,

overall height, and eye height of the participants were recorded. Then, the participants were taken to the experiment room where they were asked to wear the fiducial marker and participants not wearing glasses were asked to wear safety glasses for both interactions. The participants were then read the interaction script and the movable wall was closed before beginning the interaction with robots.

2) *Interaction with the Robots*: Each participant interacted with both the Hummingbird and the Double. The interaction order was counterbalanced where participants (odd female, even male) were presented with the Hummingbird first and then the Double while other participants were opposite. The Double had a safety zone from 45cm (1.48ft) to 10cm (0.33ft) and the Hummingbird had a safety zone from 60cm (2ft) to 35cm (1.15ft), which would cause the robot to stop autonomously if not instructed to do so. This information was omitted so that participants would stop the robot instead of letting it stop on its own, but was required by IRB to ensure that we did not strike any participants.

During each interaction the robot approached the participant directly (see Fig. 2) with a speed of 20cm/s for the Hummingbird and approximately 21.2cm/s for the Double (due to the inverted pendulum design, it varied from 20 to 27.5cm/s). The Double presented a blank iPad screen, with the camera still visible at the top (see Fig. 3), while the Hummingbird had no visible camera but did maintain a single direction of flight throughout the approach.

3) *Survey Evaluations*: Participant feelings were collected in the pre-questionnaire through use of the Positive and Negative Affect Schedule (PANAS) [36] examining feelings for the past few days and current day, as well as the Negative Attitudes towards Robots Scale (NARS) [37].

In the first post-interaction survey, the PANAS was administered to assess any change in positive affect (PA) or negative affect (NA). Once the participants were done with the questionnaire, they were taken back into the experiment room to interact with the second robot.

4) *Post-Interaction*: After the interaction with the second robot, the participants were taken out of the experiment room again and asked to fill out a post-questionnaire to assess the information on their affect after interacting with the second robot, as well as notes about the experiment in general and the interactions with the robot. After the post-questionnaire, participants were interviewed in the experiment room to collect data on their feelings during the experiment, the positive and negative experiences they had, and their comments on the experiment which will be summarized in Section IV-E.2.

E. Analysis and Results

This section will initially present the numerical analysis on the distancing and PANAS data, before discussing possible trends in the data through the use of qualitative responses from the post-questionnaire or interview. Due to the non-normal distribution of participant data, a Wilcoxon Signed Rank test was run on both the distance data and the PANAS questionnaire responses to understand participant comfort with the Double versus the Hummingbird.

1) *Numerical Results*: The hypothesis was supported by the statistical tests, suggesting that participants were more comfortable interacting with the Double than the Hummingbird when comparing distance and reported stress (NA).

A Wilcoxon Signed Rank test was used to compare the different requested robot stop distance for each subject between the Hummingbird and the Double. The test suggests that the distance for the Hummingbird was significantly larger than the Double ($W(16) = 5$, $p < 0.001$), with an approximate difference of 25.8cm and a 95% confidence interval of 14.5 to 39.0cm, based on a mean distance from the Hummingbird of 65.5cm and the Double of 36.5cm.

A Wilcoxon Signed Rank test was also used to compare each of the PA (sociability) and NA (stress) [36], specifically the difference of affects in the Post-Interaction Questionnaire from the initial “Today” measurement in the Pre-Questionnaire for each participant in each interaction. This will reveal overall affect (sociability and stress) changes and whether these suggest a significant difference between the ground vehicle and sUAV. The test suggests that the PA of participants was unchanged in the different robot conditions when compared to the initial measurement in the Pre-Questionnaire. When looking at the NA of the participants, the test suggests that the participants reported higher distress after interacting with the Hummingbird than with the Double ($W(16) = 78$, $p < 0.01$). The average “Today” value for NA was 12.2, average NA after interaction with the Hummingbird was 13.4, and after the Double was 10.8. The average difference of NA between the Hummingbird and the Double was 3.5 (95% confidence interval from 2 to 5).

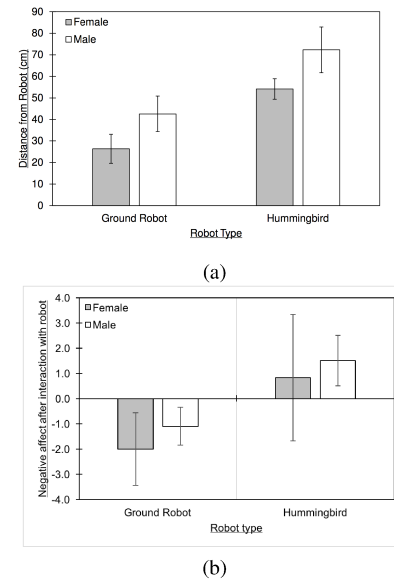


Fig. 4: Mean and standard error values for minimum distance (Fig. 4a) and NA difference from baseline (Fig. 4b) as affected by gender.

One unsurprising trend, which was not significant based on the differences shown in Fig. 4 but will be discussed here in relation to the literature, is the increased comfort felt by female participants depicted by close approach distance and less negative affect in comparison to male participants. This

reduced distance in female participants has been previously reported by [24], [39] in approach distance studies.

An additional note on the distancing, six participants (P4, P7, P9, P10, P11, and P15) watched their feet during interaction with the Double (presumably to see if it would hit them) and six participants (P4, P7, P8, P9, P10, and P11) did not stop the Double before it reached 10cm (minimum interaction distance). Three participants (P9, P10, and P11) did not stop the Hummingbird before it reached the minimum interaction distance (with slow down starting at 60cm and occurring until 35cm, where the participants could still “stop” the robot in this zone).

2) *Qualitative Results:* Participant reactions expressed curiosity, engagement, and also led to some recommendations for follow-on work, which will be discussed further in Sections V-C and V-F. Overall the participants found the lack of “face” on the Double to be distracting. When considering the Hummingbird, the participants commented on the air movement and noise generated by the vehicle, which they mentioned in reference to decreased comfort. Finally, the general comments pointed to overall feelings of safety and controlled environment, while also expressing interest in factors suggested for future studies (e.g., different heights in approach and the impact of sound on comfort).

Double:

- P8: “I was half expecting the screen to pop on with a face.”
- P16: “It was good that the screen was closed, it made me feel like I was supposed to interact with the robot. I did think that the person behind the screen was controlling the robot though, so that may have influenced when I told it to stop.”

Hummingbird:

- P3: “The more the user feels the air from the props the more uncomfortable I’d suspect they’d feel.”
- P7: “I don’t like the blades whirling at neck height reminds me of SAW movies. I don’t think the drone would be so bad if it were above me, but neck height was off putting.”
- P12: “I felt more nervous with this robot because it felt less secure or erratic being in the air rather than the ground. It all seemed less avoidable if it weren’t to stop. It could follow me more easily.”
- P16: “Can we make drones quieter? I think that adds a lot to the uneasiness I feel. It feels significantly more dangerous with the propellers.”

General:

- P3: “Exposure to the same robot multiple times would yield far more interesting results.”
- P10: “If it was put outside I would not touch it, I would keep some distance, but here I am sure that I am safe enough, and I feel comfortable”

V. DISCUSSION

Findings from the study supported the hypothesis which will be discussed in this section. The initial hypothesis that

participants would display different comfort with ground versus aerial vehicles was confirmed through an increased distance and stress when interacting with the sUAV, as well as statements about noise and wind decreasing comfort.

A. Relation to HRI in General

When considering the participant comfort, as well as trends based on participant gender, these results are consistent with prior work in HRI. The distance observed between the participants and the Double was similar to those seen in [25], [29], which is particularly interesting when considering that the robot in [25] weighed around 150 kg (22 times as much as the Double). It should be noted that the distances are still difficult to directly compare due to possible differences in the environment ([25] looks larger than this testbed, which could have resulted in increased distance here). The trends for female participants to prefer smaller personal space, and the observed reduced stress in interaction, support prior findings by [24], [39] of different preferences by gender.

B. Relation to Previous Distancing Studies with sUAVs

While these results cannot be directly compared to previous work due to different platforms used and different ceiling heights, this work provides the first free-flight distancing study and also suggests that the original work by Duncan and Murphy [10] may have been influenced by the artificial stability or presence of a blade guard. The mean participant distance in this study was outside the safety zone of 60cm in [10] and a significantly smaller platform was used in the current study. There is the potential that the blade guard also reduced the distance in the Duncan and Murphy study, but this is left for previous work.

C. Manipulation Considerations

The primary manipulation concern in this study is the participant reports on details from this study. The primary participant reports regard the lack of stimulus on the Double screen and the perception of safety by the participants. When designing the study, a conscious decision was made to reduce the possible distraction to the participant by turning the screen off, but this lack of stimulus was noted by the participants (see Section IV-E.2) and at least one perceived that a person was still controlling the robot. Participants in the study also reported that they felt they were not in any danger in these interactions, even though one said they would not approach the robots outdoors, which might be a failure in the authenticity of interaction as defined in [35].

D. Limitations

The limitations of this study are: minimum distance imposed by IRB, possible novelty effects due to single-shot interaction, broad applicability of results from a single sUAV platform, simple flight path, and perceived risk by participants. Other HRI studies, notably [25], [10] used safety distances, but these can artificially limit the applicability of results so future studies may consider using safe platforms to further understand personal space. The single-shot interaction

was recommended by other studies [18], [23] and the impact of multiple approaches was not described in others [25], so the impact on distance remains an open question. As noted above when comparing to the work by Duncan and Murphy, distancing studies are hard to compare, so testing in the same testbed with platforms of multiple sizes is also left to future work. When considering the prior work in robot design and the findings by [33] on robot animacy, the relatively simple flight paths employed here may have led to a perceived lack of intelligence or lack of participant engagement. Finally, the participants did not seem to perceive risk from the platforms, which might be mitigated in the future through more realistic interactions as suggested by [35] and [40].

E. Research and Design Implications

The observations here suggest that there are differences in comfort when interacting with aerial versus ground robots. As this work doesn't fit neatly within the zones defined by Hall in [14], interactions with aerial vehicles have the potential to be more similar to animal interactions (and might fit better in Hediger's flight and critical zones [15]). This is recommended for consideration in future work, as the current study shows comfort within unsafe interaction distances.

This work is an early starting point in the open and exciting field of human-sUAV interaction and hopes to suggest future areas of work, while also noting where prior work may not directly apply. The significant difference in personal space maintained between the sUAV and the ground platform is promising, but leaves more questions than answers. One major concern is the relatively small space maintained from a sUAV without blade guards, which raises questions about perceived safety and the potential for blade guards to reduce space from a still dangerous platform like the one used in [10]. Additional questions remain about the perception of sound (higher pitched as the sUAV gets smaller) and wind movement created by the blades (dependent on blade design and size), which can only be investigated with further studies in this area. Additionally, the slow speeds recommended from the human-human studies are not ecologically valid in most expected uses of sUAVs so realistic flight paths and speeds should be tested in the future. Finally, there are questions about the appropriate height or flight path that could be based on operational use, height of the participant, and environment of operation, which will also provide valuable insight into the perception of these vehicles in actual use. It is hoped that this paper will provide a standardized experimental space, design, and distances from which future studies can be informed.

F. Future Work

It is recommended that future work consider: whether findings from human-human interactions map to human-sUAV interactions, additional factors that are relevant to sUAVs that were not available to human or ground robot interaction, and conducting studies with a larger sample size in order to explore personal differences.

The most obvious next step for HRI in considering the mapping from human-human interactions is to consider outdoor studies to reduce the perceived safety in the lab. It is also recommended to conduct a study to understand the impact of two versus three interactions on participant responses, since three interactions would allow a better understanding of the relationship between scaling factors (e.g., height changes, vehicle size, etc.). When considering an outdoor study, replication of [23] could be conducted as evidence on the impact of the environment and this study might again compare both ground vehicles and sUAVs to understand the implications for the broader HRI community.

When investigating human-sUAV interactions, there are factors which can be changed that would normally be fixed in human-human or human-ground robot interactions. Initial studies should investigate the impact of height changes of an sUAV on personal space and whether people feel safer with a higher or lower approach before changing to an eye- or arm-level interaction height. Another important avenue for exploration is the impact of size, which has been somewhat investigated within human-human interaction with [22] mentioning that the taller experimenters were chosen to have similar body shapes (thus higher weights). When considering size in sUAVs, this will change the weight, air movement, and sound (both amplitude and pitch) of the interaction, so researchers should work to change each of these independently when possible to understand the interactions between these factors.

Finally, a larger sample size (even 30 participants) and full body tracking of the human participants would allow more inferential statistical comparisons and more information about how personal differences may impact comfort. If participants were outfitted with motion tracking on their heads and extremities, then their postures could be better tracked and methods from psychology and HRI could be used to better infer emotional state in real-time rather than as a post interaction metric.

VI. CONCLUSIONS

In this work, we explored human comfort in interacting with sUAVs by comparing approaches of a ground vehicle and sUAV at the same height. If human-human and human-ground robot studies mapped directly to aerial vehicles, it would be anticipated that the distances would be similar when comparing different vehicles (of the same height), which was not true in this case. In human-human studies, it was not found that testing multiple conditions in a single visit impacted results due to the reflexive nature of distance perception, but it is unclear that this is the case with aerial vehicles. The findings here suggest that ground robots and sUAVs may cause people to distance in different ways, and that more work should be done with similar environments and interactions for expected deployments. This work did support the need for research in distancing if aerial vehicles are to be used in public spaces due to both the small distance maintained in this study (difficult to maintain outside a laboratory) and the variance in reports on sUAV interactions.

The results from this study raise questions about how people will perceive the safety versus comfort tradeoff with these vehicles as they become better incorporated in public safety uses by police or other emergency responders and present limitations of our understanding of these vehicles as social platforms, but also provide baseline measurements for future work in this relatively unexplored area.

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