8-2013

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Duncan, Brittany A. and Murphy, Robin R., "Comfortable Approach Distance with small Unmanned Aerial Vehicles" (2013). *CSE Conference and Workshop Papers*. 240.

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Comfortable Approach Distance with small Unmanned Aerial Vehicles

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Abstract—This paper presents the first known human-subject study of comfortable approach distance and height for human interaction with a small unmanned aerial vehicle (sUAV), finding no conclusive difference in comfort with a sUAV approaching a human at above head height or below head height. Understanding the amount, if any, of discomfort introduced by a sUAV flying in close proximity to a human is critical for law enforcement, crowd control, entertainment, or flying personal assistants. Previous work has focused on how humans interact with each other or with unmanned ground vehicles, and the experimental methods typically rely on the human participant to consciously express distress. The approach taken was to duplicate the experimental set up in human proxemics studies, while adding psychophysiological sensing, under the hypothesis that human-robot interaction will mirror human-human interaction. The 16 participant, within-subjects experiment did not confirm this hypothesis. Instead a sUAV above height of a “tall” person in human experiments (2.13 m) did not produce statistically different heart rate variability nor cause the participant to stop the robot further away than for a sUAV at a “short” height (1.52 m). The lack of effect may be due to two possible confounds: i) duplicating prior human proxemics experiments did not capture how a sUAV would likely move or interact and ii) telling the participants that the robot could not hurt them. Despite possible confounding, the results raise the question of whether human-human psychological and physical distancing behavior transfers to human-aerial robot interactions.

I. INTRODUCTION

As small Unmanned Aerial Vehicles (sUAVs) become more commonly used around the general public, it is important that the Human-Robot Interaction (HRI) and public safety communities understand how people will react a sUAV for applications such as crowd control, entertainment, or flying personal assistants.

This paper presents from the first known study of comfortable approach distance and height for general human-robot interaction with a sUAV. The specific research question addressed in this study is: *How closely will an uninformed participant allow a sUAV to approach before feeling uncomfortable or anxious, and does this distance change based on the height of the vehicle?* Since Hayduk [6] defines personal space as “the area individual humans actively maintain around themselves into which others cannot intrude without arousing discomfort,” these distances at which participants

begin to feel uncomfortable will be referred to as *personal space* or *comfortable approach distance*. This study measured the difference in personal space by measuring at what distance people, who were standing still, would ask a sUAV to stop based on two different height conditions, corresponding to a short person (1.52 m) and or a tall person or low ceiling (2.13 m). The expectation was that sUAVs flying at the “tall” height would result in larger personal spaces, just as shorter people prefer to stay at a further distance from taller people. An experiment replicating prior psychological studies was conducted with 16 participants in a within-subjects design, and used the traditional stop distance method but added psychophysiological data, notably heart rate variability, as a convergent measurement in comfortable approach distancing.

II. RELATED WORK

Psychology, human-robot interaction, and animal studies have investigated the impact of height on the size of a person’s personal space. Psychology has shown that lower ceilings increase the personal space. Human-robot interaction has explored influences on personal space such as whether a ground robot approaching a person produces a different result than a person approaching a ground robot [8], if robot experience changed the space [9], and the impact of gender and age [10]; however only Oosterhout and Visser [11] appear to have directly considered the height of the robot in a distancing experiment. The experiment in section V builds on the traditional stop distance technique for measuring the size of personal space and adds a participant survey and measures of heart rate variability; the rationale for using heart rate variability is described below. Animal studies were excluded from this paper because they have not been as well examined in the context of the CASA model, on which this study was based.

A. Psychological Studies

Psychological studies have explored how personal space changes as a function of the relative height or approach angle of two humans, or the height of a ceiling. Two human studies [4], [5] and one robot study [11] suggested that tall agents require more space than short agents when interacting with adults, this is depicted in Figure 1. The studies typically rely on the *stop distance technique* for measuring the size

*This work was supported by a National Science Foundation Graduate Research Fellowship

Fig. 1: Figure showing the relative difference in personal space with experimental participants of two different heights.

of the preferred personal space [1] and an approach speed of 0.2 m/s [6]. Hayduk [6] determined that personal space only shrank about 8% when participants knew it was being measured, thus experimental results tend to be smaller than would be expected in normal interactions. The experiment described in section V replicates the ceiling studies tested using the standard proxemics study stop distance technique [1] and approach speed [6].

Three studies on proxemics focused on how personal space changes as a function of an approaching person's height, approach angle, or perceived intent; this is relevant because a sUAV may be treated as a tall person. Kinzel conducted a seminal study in 1970 that showed that violent prisoners required almost four times as much personal space as non-violent prisoners and that this increase was focused in the rear approach zones [1]. The study also contributed the *stop distance technique*, where the prisoners were told to stand in place while they were approached by an experimenter and then say "Stop" when they were uncomfortable being approached any closer. Caplan and Goldman [4] performed an observational study in a train station to determine whether height had an effect on space interactions in public places. Four experimenters were used: a tall male (1.88 m), a short male (1.65 m), a tall female (1.8 m), and a short female (1.57 m). It was determined that short people had their personal space invaded more frequently than tall people; this suggests that a person may yield space to a "taller" sUAV but with less comfort than if they were being approached by a "shorter" sUAV. Hartnett [5] also examined the effect of tall (1.91 m) versus short (1.63 m) experimenters on comfortable distance, but using a reversal of the stop distance technique where the participant approaches the experimenter and stops when they are uncomfortable. There was a significant difference based on the height of the experimenter and the position (sitting or standing) of the experimenter during the approach. The angle and perceived intent are not considered in Sec. V, deferred to future experiments.

One study on proxemics examined the influence of ceiling height on personal space; this is relevant because a sUAV

may be perceived as a type of vertical barrier. Cochran and Urbanczyk [2] used the stop distance technique to compare comfortable approach distances for ceilings of different heights, low (2.13 m) and high (3.04 m). The findings from this study was that a lower ceiling resulted in a larger personal space (1.03 m vs 0.72 m).

B. Human-Robot Interaction Study with Ground Robots

One human-robot interaction study has examined the effect of ground robot height on the size of a person's personal space, which is relevant if a sUAV is viewed as the equivalent of a person or as commanding a person-sized cylinder. Oosterhout and Visser [11] suggests that a taller robot increases the person's personal space. They examined the effects of robot height and person age on HRI with two robots, Mobi Sr (1.75 m) and Mobi Jr (1.12 m). This study was conducted in a free setting during an arts and technology festival, and subjects were not informed about the experiment. Ages were estimated, but showed that children and teenagers approached Mobi Jr more often than Mobi Sr and that adults were seen more often with Mobi Sr. The difference in distances showed that adult females, short robot interacting with adults, and tall robot all commanded larger personal spaces. Women preferred a distance of 2.32 m, while men distanced at 0.93 m. The short robot interacting with adults generally had a zone of 2 m, rather than 0.91 m from the tall robot. The overall averages were 0.38 m and 0.58 m for short and tall robots respectively.

C. Heart Rate Variability as an Additional Measure

Heart rate variability (HRV) is a method of considering the changes to heart rate over time by comparing the ratio of low frequency power (reflective of sympathetic arousal) to high frequency power (reflective of parasympathetic arousal, or vagal modulation) [12]. This method has been used by [13], [12], and [14] to measure anxiety and stress. Delaney and Brodie [12] verified that the increase in HRV was reflective of both self reports and physical tension. These results indicated that a "psychological stress test is effective in provoking a defense-arousal reaction". In the Computer-Human Interaction (CHI) community, HRV has been used to test mental workload for interface design. Rowe, Sibert, and Irwin [15], in their study of a aircraft control tower interface, state that "HRV appeared to indicate the point at which user capacity to process targets was exceeded." Within the HRI community, Rani and Sarkar [13], [16] have used HRV as a measure of human anxiety in order to facilitate better responses from a helper robot and identified a relationship between self-reported and measured anxiety levels.

III. APPROACH

The approach taken in this study is to apply the *Computers are Social Actors (CASA)* model created by Nass, Steuer, and Tauber in [17] presented a set of studies that show humans interact with a computer as a social agent. CASA has been extended to ground robots and confirmed by several HRI studies with UGVs, most notably [18], [19]. CASA may

Fig. 2: A scale drawing of the room used in this study, with the subject shown as S and the robot shown as R.

apply to sUAVs if sUAVs are viewed as human or animal-like. A human-like sUAV would be treated like there is a person occupying the space under the vehicle, essentially the sUAV occupies a virtual cylinder below it. If CASA does apply then a sUAV flying at the height a tall person should have the same effect on a person's personal space. In this case, a "tall" sUAV would produce a larger personal space measured spatially as a larger stop distance, and higher HRV.

The CASA approach leads to the following three hypotheses:

- *Hypothesis 1:* On average, tall robot and short robot conditions will result in different distances from the robot.
- *Hypothesis 2:* On average, tall robot and short robot conditions will result in different levels of heart rate variability.
- *Hypothesis 3:* On average, tall robot and short robot conditions will result in different levels of negative affect and stress, as measured by the post-interaction surveys.

IV. TESTBED

The testbed consisted of a room set up to replicate the Cochran and Urbanczyk study on how vertical space (ceiling height) affects distancing in psychology [2], with modifications due to the physical limitations of the space, and a sUAV mounted on an approach platform that controlled the height, approach angle, and approach speed. Participants were placed in the room at a taped location facing the robot in the opposite corner which would move to them. As shown in Fig. 2, the line of robot movement was at a diagonal in the room following [2], but modified due to the constraints of the ceiling.

The testbed was built inside a classroom and replicated the size and materials used for [2] and the height of the ceiling

from [3]. [2] was chosen because the environment was used for two different distancing tests based on ceiling height and it was a single approach angle environment. [3] was a multiple angle approach environment and the HRI environments were not described in enough detail to replicate. Black drapes hanging from the ceiling and weighted to the floor created a test room measuring 4.83 m (15.8 ft) by 3.51 m (11.5 ft), as shown in Fig.3a. The height of the classroom ceiling and the need to mount the robot approach platform prevented the ceiling height from being 3.05 m nor 2.13 m, so instead 2.56 m was used with the expectation that the distances seen would fall between the two measured distances reported in [2], but would still leave us enough space to test the case where the robot was considered as a ceiling.

An AirRobot AR-100B (Fig.3a) was mounted on a custom approach platform (Fig.3b). The AR-100B is a quad-rotor platform with a weight of 226.8 grams (2 lbs) and a diameter of 1.02 m (40 in) used extensively by the US military. It was chosen for this experiment for three reasons: i) it has a safety hoop that allows for safer indoor interactions than a model with exposed blades, ii) it is representative of sUAVs that are being purchased by law enforcement, and iii) it has a custom yellow body that makes it more visible than an all black model. The robot was attached to an approach platform which controlled its height, approach angle, and speed while flying and had a mechanical stop to prevent the robot from hitting the participant (Fig.3c). The platform consisted of a robot mounting bracket and a rail system. The mounting bracket consisted of a plywood fixture with telescoping PVC pipes to attach the robot and change its height, the rail system was built from 1.5 in steel plain slotted angle and suspended from the ceiling using threaded rod with a timing belt and small motor to move the platform at 0.2 m/s. The rails and platform are pictured in Fig. 3b.

V. EXPERIMENT

An experiment was run in order to determine whether the distancing observed from psychology and UGV studies would apply to sUAVs, that is, will a "taller" sUAV require a larger space than a "shorter" sUAV?

A. Study Design Overview

A within-subjects design was used for this study for two reasons: i) to have the best possible comparison for the heart rate variability data and ii) to allow a direct comparison of distance data from each participant. The two conditions in this study were: "tall" robot, which is to say the robot suspended with the top of its hat (tallest part of the robot excluding antenna), at 2.13 m (7 feet) and "short" robot, which had the top of its hat at 1.52 m (5 feet). Subjects were counterbalanced on robot order in order to determine the effect of novelty, habituation, and repeated measures. Before interaction and after consent, the subjects' height and eye height were measured, the psychophysiological sensors were applied to the participants, and a survey was completed. After the sensors were applied, the participants were held in the waiting room for a minimum of 5 minutes as a baseline

(a) Picture of the AirRobot AR-100B in the draped room, approaching a subject, and suspended from the platform.

(b) A picture of the rails and platform mounted to the ceiling.

(c) A diagram of the platform setup.

Fig. 3: Platform design.

measure, even if they completed the survey before this time was up. The robot interactions took place in the experiment room that was described above. Another survey and baseline measure were completed after the interaction, followed by the second interaction. Finally, participants completed another post-interaction and post-experiment survey during the final baseline measure, the psychophysiological equipment was removed, and an interview was conducted. All aspects of the interactions and interview were both audio and video recorded.

B. Participants

The participants for this study consisted of 16 people (8 male and 8 female) from the Texas A&M University faculty, staff, and student community with an average age 34 and a standard deviation of 14 years. All participants had

completed at least some college and had video game experience. Only one participant was not a pet owner. Thirteen of 16 participants had robot experience, with five participants reporting that they owned a robot. The average height of participants was 1.74 m (5.7 ft), with a standard deviation of 10.16 cm (4 in); all fit within the range for responding to a “tall” and “short” sUAV.

C. Measures

In order to gain convergent validity, five measures were used to examine subjects’ anxiety with robot approach: distance, psychophysiological, surveys, interviews, and audio and video recordings. Distance and psychophysiological response were the primary measures with the surveys, interviews, and recordings as supplementary data to be used as needed.

Distance was the original measure from Kinzel [1] and was used in many of the psychology and HRI studies [2], [3], [5], [8], [9], [10], [11]. This measure was limited by safety, so the minimum allowable distance was 0.6 m (2 feet) to limit the ability of the participants to touch the blades of the robot. Distance was measured from the frontmost portion of the robot, which is the safety hoop, consistent with Walters, et al. [9].

Subjects were connected to psychophysiological equipment from BIOPAC Systems to measure their heart rate data, skin conductance, and respiration. Heart rate data was analyzed for heart rate variability after being measured using a Pulse Plethysmogram (PPG) sensor, a BIOPAC TSD200 PPG transducer with the PPG100C amplifier. Skin conductance was measured using a set of two Electrodermal Activity (EDA) sensors, BIOPAC Skin Resistance transducers (TSD203) with the Galvanic Skin Response (GSR100C) amplifier, and was not analyzed for this paper, as it was expected to be used to support the difference in distance results. Respiration was measured using the BIOPAC Respiratory Effort Transducer (TSD201) with the Respiration amplifier (RSP100C) and was not analyzed for this paper, as it was expected to be used to support the difference in distance results.

Two of the three supplementary data sets were used to try to determine the negative results. A short, six question interview was conducted after all surveys and interactions were complete in order to get more in-depth answers about feelings toward the interactions, thoughts about the robot, and the experiment in general. The informal analysis of trends in answers was used to help explain the negative results. All interactions in the experiment room were recorded from 3 cameras and 2 microphones, while only the interview was recorded in the waiting room using both audio and video. The audio and video was used to confirm the transcribed interviews. Participants took four surveys i) a pre-survey with demographic information including robot and pet experience, personality questions, state, and affect information, 2) a post-interaction survey after interaction 1, 3) a post-interaction survey after interaction 2, and 4) a post-survey over the

entire experiment. The surveys were not analyzed because the primary data set was sufficient.

D. Data and Analysis

The data did not confirm either hypothesis 1 or 2. The results of the heart rate variability (HRV) and robot distances were not statistically different for the two interactions by a two-tailed t-test and repeated measures ANOVA. However, there was a significant difference between the interactions and the baseline. The p-values from the repeated measures ANOVA are presented in Table I, with the significant values ($p < 0.10$) shown in bold.

TABLE I: P-values of the Repeated Measures ANOVA on HRV

	Before	Tall	Between	Short	After
Before		0.0018	0.0285	0.0042	0.0328
Tall	0.0018		0.0224	0.2788	0.0996
Between	0.0285	0.0224		0.1213	0.8424
Short	0.0042	0.2788	0.1213		0.2032
After	0.0328	0.0996	0.8424	0.2032	

1) *Hypothesis 1 not confirmed: No Difference in Distancing in Interactions:* A two-tailed t-test indicated no significant difference between the distances in the tall interaction versus the short interaction, as depicted in Figure 4, but the distances measured will be described below. Only six participants of 16 asked the robot to stop before it reached the 0.6 m stopping point, with two of the participants saying “Stop.” before the robot stopped itself, but it actually stopping at 0.6 m. In both of these cases, the participants stopped the robot in both conditions. Two other participants stopped the robot in both conditions stopped it at 0.7 m for both participants for the short condition and at 0.8 m and 0.9 m for the tall condition. The final two participants stopped only the short robot at 0.65 m for both.

2) *Hypothesis 2 not confirmed: No Difference in Heart Rate Variability in Interactions:* Using both the repeated measures ANOVA and a two-tailed t-test, there was no significant difference between the heart rate variability readings for the tall robot interaction and the short robot interaction.

3) *Difference in Heart Rate Variability between Interactions and Baseline:* The data did produce one surprise, suggesting that the participants experienced more anxiety about the surveys and interviews than the actual interactions with the tall robot, but the same claim could not be made for the short robot. The heart rate variability readings were compared for each part of the experiment (before-interaction, tall robot, between-interaction, short robot, and after-interaction) using a repeated measures analysis of variance (ANOVA). There was a significant difference between the before-interaction baseline HRV and HRV readings for the interactions, both tall and short, ($p < 0.05$). This result would indicate that the participants experienced more anxiety about the experiment than the actual interactions with the robot. Both the between-interaction ($p < 0.05$) and after-

Fig. 4: Figure of the AirRobot AR-100B approach distancing at the two different heights, scaled to mean participant height. With cylinders to represent their ownership of the space below them.

interaction ($p < 0.10$) baselines showed a significant difference for the tall interaction, but not the short interaction.

VI. DISCUSSION

A. Possible Problems with Experimental Design

The experimental design, while appropriate for the psychology studies was not realistic for sUAV interaction due to four factors: (1) lack of realistic setting, (2) the novelty of the interaction, (3) the briefing on safety, and (4) the assumption of product safety.

The psychology research that showed an 8% decrease in personal space when being observed [6] and the use of similar room design techniques led to a belief that this experiment should give us similar results, but the use of a rail and platform setup with the robot seems to have been a distraction to the subjects. One quarter of the participants explicitly mentioned the platform or the lack of flight in the post-interaction interview.

When asked about their feelings in the post-interaction interview, the most common responses were: interested (7), curious (4), and excited (4). Participants also mentioned that they “just wanted to look at it” or, as reported by two participants about the “tall” robot, “didn’t need to stop it because it was above my head.”

As a part of the IRB consent process, we told participants that during their participation in the study they would encounter “no more risk than [they] would come across in everyday life.” We went on to describe that:

“There may be minimal risks from the moving parts on the robots. This risk has been minimized by mounting the robot on a secure platform.”

The fact that the safety was stated so explicitly may have impacted the results by implying safety of the robot in general, rather than in this specific interaction.

The final problem with the experimental design was partially identified by the authors in the production of “A Midsummer Night’s Dream” in 2010 [20], that problem is that people assume that anything they will interact with is safe until explicitly told or shown otherwise. In the case of “A Midsummer Night’s Dream”, the actors assumed that the AirRobot was as safe as the small toy helicopters, even after they were told that it could hurt them, until they were told that it is known within the robotics group as the “flying weedwacker of death.”

B. Heart Rate Variability as a Novel Measure

HRV is a novel measure for anxiety in a distancing experiment, though it has been used previously in HRI, CHI, and psychology studies. It did not produce significant differences within the conditions, but did show a change from the baseline measurements and would be recommended for future studies.

While the HRV was not statistically significantly different between the conditions, it reflected a lack of anxiety in the interactions when compared to the baseline taken before the participants were shown the robot. This is an interesting finding because it was anticipated that a sUAV might be intimidating to subjects from the general population due to the noise and the wind produced from the exposed blades.

C. Recommendations

Recommendations for future research include: possible deception studies, outdoor free-flight studies, or approach distance studies. Deception studies could be conducted by discussing the robot as an unstable prototype, or even by not mentioning the safety of the experimental design. Outdoor free-flight experiments, even if preprogrammed, would have to contend with wind and how that would effect the repeatability of the approach and the safety of the participants, but would also give the best representation of a true interaction. Approach distance experiments, where the participant approaches the robot, have been shown to give the same distances as stop distance and would allow the participants to get closer without the experimenter being able to stop them easily and thus presents a challenge of keeping participants safe from themselves in regards to touching the robot.

Recommendations for experimental protocols would be to potentially include an “interaction time” before the experiments begin to allow the participants to get a closer look at the robot, which might keep them from being as curious about the robot and allowing it to approach more closely without them being nervous so that they could get a better look.

VII. CONCLUSIONS

The 16 person study did not produce statistically significant evidence that the height of a sUAV directly approaching a person influenced the size of personal space, measured either with the traditional stop distance metric or the heart rate variability physiological metric. A “tall” sUAV did

not appear to intimidate participants, nor was a “short” sUAV allowed to approach more closely. The experiments may have been confounded by the lack of realistic setting and interaction as well as the IRB protocol requiring the participants to be told that they were safe from the robot. However, the negative results may indicate that the CASA model may not apply to sUAVs despite its applicability to UGVs. The convergence of the stop distance results with the HRV results reinforce the opinion that HRV is a useful measure for HRI.

ACKNOWLEDGMENTS

The research was conducted using the HRI module of the RESPOND-R mobile test instrument (NSF MRI Grant CNS-0923203). The authors wish to thank Adrian Jimenez Gonzalez, Tanner Perkins, and Edgardo Calzado for their assistance in building and testing the experimental setup.

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