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Evaluating Distances in Tactile Human-Drone Interaction

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Abstract— **The increasing autonomy and presence of Unmanned Aerial Vehicles (UAVs), especially quadrotors, in everyday applications requires in-depth studies of proxemics in Human-Drone Interaction (HDI) and novel methods of user interaction suitable for different distances. This paper presents a user study (N=32) that evaluates proxemics with a miniature quadrotor (92 mm wheelbase) from four directions (front, back, left, right) in a seated setting investigating preferred approach directions and distances in future home or workplace scenarios. The goal of this study is to determine if humans are willing to allow flying robots of that size and mechanical appearance to approach close enough to enable tactile interaction. Moreover, the participants' inclination to physically interact with the quadrotor is examined. Studies evaluating proxemics in HDI are highly dependent on repeatable results and actually flying robots. In most comparable studies, the quadrotors used did not fly freely or at all, but were moved, manually controlled, or flew barely repeatable trajectories due to unstable onboard navigation. Only few studies have used pose estimation systems that ensure smooth and reproducible trajectories and thus reliable findings of the studies. For this reason, in addition to the presented study and its results, an insight into the used testbed is provided, that also integrates full skeleton pose estimation rather than tracking participants with only a single marker.**

I. Introduction

Over the last 20 years, quadrotors made their way from a niche hobby over a standard platform in research to the professional and consumer area. Unmanned Aerial Vehicles (UAVs), that include quadrotors, have grown to play an instrumental role in daily applications. Due to their simplicity and affordability they are being utilized as a tool in logistics, first response, reconnaissance and surveillance, inspection of industrial facilities, construction, measuring, and aerial photography or videography. The majority of applications require human interaction. Manual control is demanding and only desired by professionals and hobby pilots. However, quadrotors are becoming increasingly autonomous, enabling the substitution of manual control with more natural interaction. In addition, the number of (flying) robots surrounding us may further increase in the future, which results in them simply no longer being manually controllable. Just as smartphones already do today, small UAVs could support us in our homes or workplaces, where humans often spend a considerable amount of time sitting. Numerous anticipated situations where humans will encounter drones offering their services require the study of proxemics in Human-Drone Interaction (HDI), as well as new interaction techniques that are more natural than using traditional radio remote controls or smartphones.

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A. Interaction

Over long distances, several gesture control approaches have been proposed for natural communication [1], [2]. At closer distances, when it is not possible for cameras to fully capture people for gesture detection, other interaction methods are required and desirable. Studies were conducted on mimic control [3], voice control [4], [5] as well as on multimodal interaction that includes hand gestures [6], [7]. Most non-contact scenarios require additional high-level sensors such as depth cameras or motion sensors. These can be permanently installed in a controlled environment, attached to the user's body [8], [9] or mounted on the quadrotor. The last option assumes that the quadrotor has enough power to carry the additional payload, which in turn usually leads to larger vehicles. At close proximity, real physical control was implemented by mounting physical buttons to a ring attached to the quadrotor [10]. Dispensing with intermediary devices or additional sensors, a virtual button metaphor was introduced in [11], which utilizes the onboard Inertial Measurement Unit (IMU) to detect taps to the quadrotor's frame und thus keeps the scale and weight of the vehicle to a minimum. But to allow for close proximity HDI, and to physically interact with the quadrotors at all, humans must grant the robots access to their personal space.

B. Proxemics

The way a robot should approach a person, e.g., to engage interaction, and at which distances humans still feel comfortable around them is studied in the research field of proxemics [12]. Proxemics originally studied the use of space and its effects on communication between humans but has been adopted by the Human-Robot Interaction (HRI) community. Interaction predominantly happens in personal space, that ranges from 0.45–1.2 m (see Fig. 1). But especially at closer distances, a natural inhibition threshold exists that humans experience when it comes to interaction with robots, whose intents are hard for humans to unterstand. The inhibition threshold is higher for flying and mechanical-looking robots than for ground-based robots or robots that have been given anthropomorphic features [13], [14].

One of the first human-drone proximity user study was conducted in [15]. Using the largest quadrotor platform (AirRobot AR100-B) of the tests discussed within this paper, this one had a safety ring attached with the diameter of 1 m. In their user study, the quadrotor was mounted to a moveable platform at the ceiling and the minimum distance allowed between the participants and the quadrotor was set to 0.6 m.

In the user study conducted in [14] an off-the-shelf quadrotor (DJI Phantom 3, distance between opposite rotor axes, or

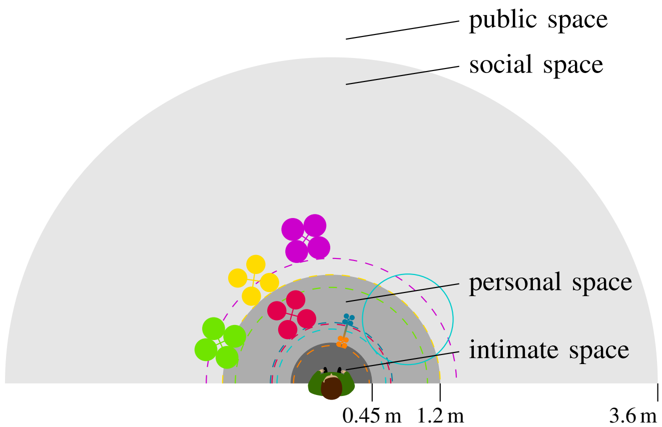

Fig. 1. Interpersonal distances (of humans) [12] (intimate space (<0.45 m), personal space (<1.2 m), social space (<3.6 m), and public space (<7.6 m)) and tolerated approach distances evaluated in different quadrotor proxemics studies: Crazyflie 2.0 stopped by hand and Crazyflie 2.0 stopped by foot in this user study. AscTec Hummingbird [13], "social" DJI Phantom 3 [14], Parrot AR.Drone 2.0 [14], regular DJI Phantom 3 [14], safety ring of an AirRobot AR100-B [15], stopped by saying "stop" in other user studies.

wheelbase $L = 350$ mm) approached participants as is ("non-social", stopped at 1.38 m) and provided with a face and greeting voice ("social", stopped at 1.06 m). Since the drone would slightly drift off and move unpredictably, it was hung on a zip-line instead of actively flying toward the participants. Moving rotor blades, the generated downwash and noise heavily influence the emotions of the participants [16], thus limiting the significance of the study.

In the user study of [13] a professional motion capturing system was used, which ensures reproducible trajectories and thus repeatable experiments. A mechanical-looking quadrotor (AscTec Hummingbird, $L = 340$ mm) was compared with a ground-based robot and was stopped at a distance of 0.66 m but with the participants experiencing a statistically observed, increased level of mental stress. The motion capturing system that was used in their study is very cost-intensive, which makes it difficult for smaller research institutions in particular to create a similar accurate test environment.

The preferred flight characteristics of an autonomous drone approaching a person were evaluated in [17]. Four parameters were examined: speed, direction, height and the final proximity to the participants. The preferred conditions resulted in the quadrotor approaching the participants at a constant speed of 0.5 m/s from the front, at a constant height of 1.75 m, with the quadrotor stopping in their personal space (1.2 m). But the authors of the study also observed a variability in the quadrotor's trajectories.

C. Motivation

Proxemics user studies involving quadrotors are highly dependent on them actually flying, as the moving rotor blades, generated noise and downwash have an important impact on the user's emotional state. The size of the quadrotor and its rotors, and whether it is equipped with rotor guards or even social features, also influences the users. All these parameters vary in the studies discussed, making comparisons difficult. But in all studies, quadrotors were either too far away [14], [17] to enable close proximity physical interaction, or the increased level of mental stress [13] would discourage the participants from interaction if they had the opportunity.

There are several strategies to further reduce mental stress in HDI and to further lower the experienced inhibition threshold. Like in [14], a quadrotor was provided with social features. But the introduction of anthropomorphic features to miniature flying robots would exceed their functional design and may not be desired because it would add to their already critical payload. When it is not possible or desired to add anthropomorphic features, robots are able to express inner state, emotions or intent in the way they move [18]. Regarding drones, that do not have other moving parts than rotors, this can be expressed in their trajectories. However, published research lacks detailed implementation and parameterization [19] or remains on a conceptual level [20]. How to convey affect in a quadrotor's flight path has been studied in [21], how to acknowledge a person by, e.g., wiggling, in [22]. Motion intent was conveyed through blinking LEDs [23], through Augmented Reality (AR) [24] or by applying principles of character animation, like anticipation, to quadrotor trajectories [25]. However, in this user study straight, smooth trajectories are used to provide a basic estimation of the tolerated proximity; the improvement of this by the above mentioned possibilities for further user studies is left for future work.

D. Structure

This paper re-evaluates the distances in HDI with a minimalist, mechanically-looking, miniature quadrotor ($L = 92$ mm) to test whether humans are willing to allow the robot coming close enough to prefer tactile close-proximity interaction over non-physical interaction. Aiming at future home or workplace scenarios, the quadrotor's approach was tested from four directions to the participants seated on a chair. This paper also provides an insight into the HDI testbed in which the user study was conducted in. It ensures accurate repeatable flights while being cost effective compared to commonly used motion capturing systems.

This paper is structured as follows: Section II introduces the testbed that was used to conduct this user study. The study itself is then described in Section III. The results of the user study are discussed in Section IV. Finally, Section V summarizes this paper and proposes future work.

II. Testbed

The low-cost quadrotor testbed *ICARUS* [26] that is used in this experiment was developed and further improved over recent years and allows tracking and control of general off-the-shelf hobby quadrotors or the Crazyflie 2.X platform in reality or simulation. Compared to other testbeds used in HDI user studies, this testbed ensures reliability of results by guaranteeing repeatable trajectories while being inexpensive.

The quadrotors are equipped with several 850 nm infrared emitters that are tracked by multiple industrial cameras equipped with according bandpass filters. The monocular

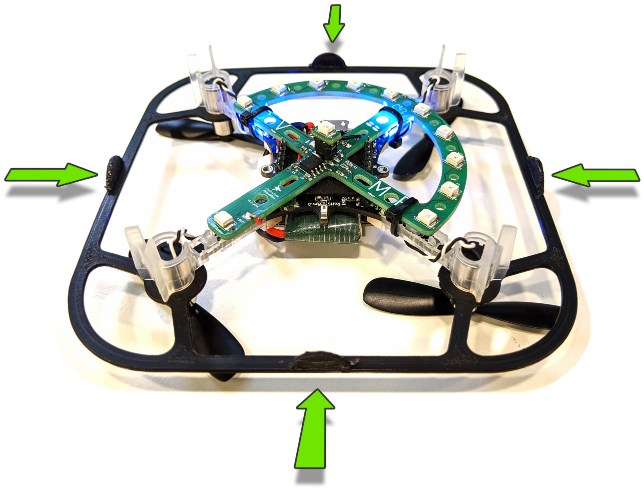

Fig. 2. Bitcraze Crazyflie 2.0 with rotors mounted upside down so they do not obscure the LEDs of the attached tracking marker. The 3D-printed frame provides tactile interaction points that are marked with arrows.

pose estimation system was presented in [27]. In the particular setup for this user study, three Ximea MQ013MG-ON USB3 hardware-synchronized, high-speed vision cameras with a resolution of 1280×1024 pixels were used in conjunction with Fujinon 1:1.2/6 mm DF6HA-1B lenses mounted to the ceiling of the flight area and filming downward. In addition, a Kinect 2 is used for human skeleton estimation. All cameras, including the color and infrared sensors of the Kinect, are registered into the coordinate system of one reference camera. The cameras are triggered at a constant rate of 100 Hz through an electrical circuit. The Kinect 2 is running asynchronously on a dedicated Windows machine that runs the official Kinect 2 SDK and multicasts UDP messages at a rate of 30 Hz containing the skeleton joint positions of up to six persons.

The measurement noise of the pose estimation system is smoothed out by a weighted average over a given time window to reduce lag that would otherwise be introduced by older poses. All poses tracked by the individual cameras are then merged and multicasted as UDP messages containing multiple six degrees of freedom poses and their timestamp. An incoming tracking message triggers the quadrotor control loop to ensure using the most recent poses and telemetry data. The skeleton joints and quadrotor poses are converted into a previously defined, global reference coordinate system and the quadrotor states are extended by numerically derived linear and angular velocities. The quadrotor states are then latency compensated by a predictor-corrector estimator [28] utilizing a quadrotor dynamics implementation as described in [29]. The battery voltage included in the telemetry data is used to compensate the thrust command for varying voltages.

Tracking and control runs on a Macbook Pro (Mid 2012, 2.7 GHz Intel Core i7), where a trajectory generator parametrizes keyframes consisting of time, position, velocity, acceleration, and orientation about the vehicle's yaw axis into a quintic polynomial trajectory that is tracked by a Model-Predictive Controller (MPC) based on the work of [30]. It uses the `ACADO` library to set up the optimization problem and the `qpOASES` library to solve it. A discretization time step of $\mathrm{d}t = 0.1\,\mathrm{s}$ and a time horizon of $t_h = 2\,\mathrm{s}$ is used. While the model parameters remain unchanged, the controller was tuned experimentally and differs slightly from the original implementation: The horizontal and vertical position error costs were left at 200 and 500, respectively. The attitude error cost was reduced from 50 to 25 and the velocity error cost was reduced from 10 to 4. The cost of thrust, roll, and pitch inputs has been left at 1 and the cost of yaw input has been increased from 1 to 10. The controller used for hovering was published in [31].

A Crazyflie 2.0, which is a flying development platform from Bitcraze, was slightly modified for the use in this experiment and can be seen in Fig. 2. We designed and 3D-printed a lightweight frame to allow for tactile interaction points at the sides of the quadrotor to prevent participants from touching the rotor blades mid-flight. Furthermore, we turned the quadrotor upside down to a "pusher" configuration. This enables the attachment of the described tracking markers used for pose estimation without the rotors obscuring the emitters. The Crazyflie runs the latest stock firmware in rate mode with onboard battery compensation disabled, as this is handled by the testbed implementation. To control the Crazyflie and receive telemetry data by software, we use the `crazyflie_cpp` library [32]. The rate of acceleration telemetry data was set to 100 Hz.

The metaphor of distinguishable virtual buttons detected in the accelerometer data of the onboard IMU of a quadrotor to enable tactile interaction without additional sensors was described in [11]. This method is used here to detect taps on the frame of the quadrotor during the experiment.

III. User Study

The user study was carried out in the *ICARUS* flight laboratory, that was described in the previous section. For this experiment, the testbed was set up in a $6.8 \times 5.9 \times 2.7\,\mathrm{m}$-sized room. The cameras were adjusted to be able to capture a flight area of approximately $4.5 \times 2 \times 1.4\,\mathrm{m}$. The complete setup is depicted in Fig. 3. In the following evaluation, we use $\bar{x}$ to denote the mean and σ to denote the standard deviation of measured values. Measured distances are given horizontally from head center to quadrotor center. If results are statistically significant ($p < 0.05$), they are underlined.

A. Participants

The user study ($N = 32$) was conducted with 11 female (34.4%) and 21 male (65.6%) participants aged 19 to 42 years ($\bar{x} = 25.90, \sigma = 5.44$). Almost all participants were from our institute, studying different branches of Computer Science (20), Media Management or Media Conception & Production (7), Mobility Management (1) or are research assistants (4). Seven of the participants have robots at home (six vacuum cleaners and one educational robot companion), 16 of them already had contact to drones prior to the test and two of them own a quadrotor.

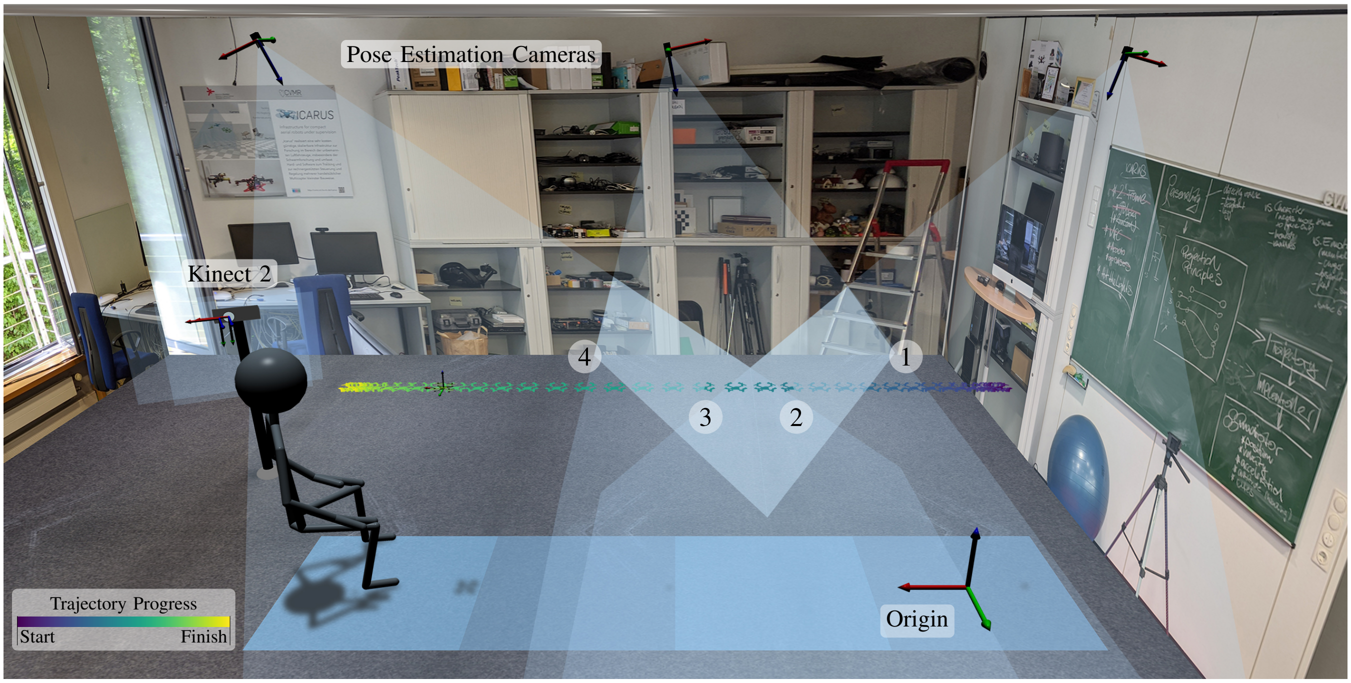

Fig. 3. Rendered scene of a session of the conducted user study: The participant is seated on a chair while the quadrotor approaches from the front, one of four tested approach directions. The participant is tracked by a Kinect 2 and the quadrotor by several cameras. Numbers mark the transitions between the fields of view of the cameras: Up to mark 1, the quadrotor is only seen by the right camera. From 1 to 2 it is in the fields of view of the right and middle camera. From 2 to 3 it is only seen by the middle camera. At 3 the quadrotor enters the view frustum of the left camera and at 4 it leaves the field of view of the middle camera and is only seen by the left camera.

B. Setting

At the beginning of each session, the participants were handed out instructions in order to ensure all of them facing the experiment with the same basic knowledge and were asked to carefully read them. The instructions contained the photograph of the quadrotor shown in Fig. 2 with arrows pointing toward the possible tactile interaction points. Furthermore, an equal backup quadrotor lay next to the instructions. The participants were given the information that a quadrotor will approach them at moderate speed and constant height in four different, sequential flights from four directions, namely from the participant's front, back, left and right, in a randomized order. The participants received the information that they could stop the quadrotor at any time from further approaching if they felt uncomfortable. They were given the choice to initiate this with a foot switch or by directly tapping to the quadrotor's frame. Thus, the participants were left to decide whether they wanted to stop the quadrotor at all, and if so, in what way. The methods to stop the quadrotor eliminate unwanted delays that could be caused by the participants having to instruct an operator to stop the quadrotor for them, as done in other proxemics studies [13], [17], [15], [14]. Furthermore, the foot switch enabled the participants to have both their left and right hands at their disposal in case they decided to stop the quadrotor by hand. The information that the trajectory would end right in front of the participant's chair and that the distance between their head and the quadrotor would be continuously monitored for safety reasons was intentionally omitted.

The participants were asked to fill out an initial form containing questions about their demographics, personality as well as their previous experiences with robots and drones in general. Furthermore, they had to fill out an initial Self-Assessment Manikin (SAM) survey [33], provided as a 5-point Likert scale in order to assess the participants' initial emotional states. The SAM scales are a pictorial rating system to obtain self-assessments of emotions along the dimensions of valence, arousal, and dominance. Values along the valence dimension range from negative to positive emotion. The arousal dimension values range from calm to excited. Along the dominance dimension values range from being submissive to being in control. The SAM test was repeated after each flight, along with questions about their wellbeing ("not well at all. . . very well") and perceived proximity of the quadrotor at its final position ("too close. . . too far"), both provided using a 5-point Likert scale. After filling out the forms they were accompanied to the flight laboratory in order to carry out the test. A session took about 20 minutes.

C. Hypotheses

The primary hypothesis of this study was that people would show different levels of affective responses and comfort with the different approach directions of the quadrotor. This was assessed by the questionnaires as well as the distance at which participants chose to stop the quadrotor from further approaching. The chosen stop method should provide information on whether individuals would voluntarily, physically interact with a quadrotor by hand.

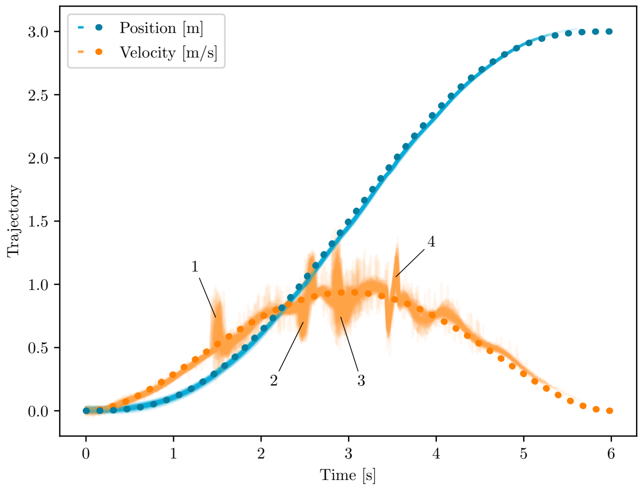

Fig. 4. The quadrotor's position and velocity along the x coordinate. Dotted lines show the reference trajectory while continuous lines show all 128 flights of this experiment. The y and z coordinates are fixed and their axes are therefore not shown. Numbers mark transitions between individual view frustums of the cameras and correspond to the numbers in Fig. 3.

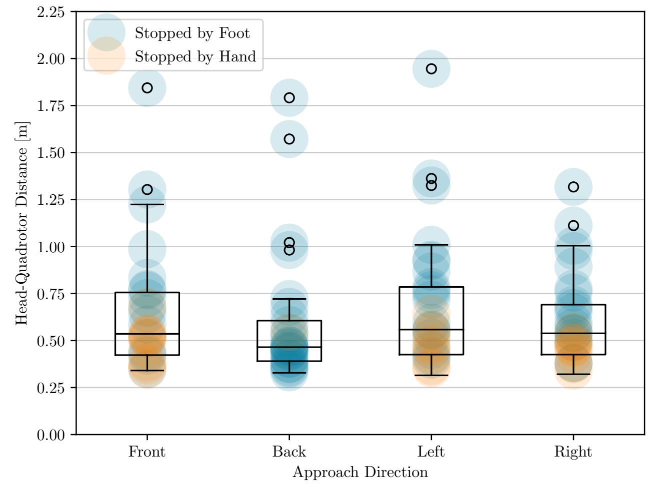

Fig. 5. Boxplots of the four approach directions including all sampled stop distances color-coded by the method of stopping the quadrotor from further approaching. Blue samples were stopped using the foot switch and orange samples were physically stopped by tapping the quadrotor's frame. Samples of flights that were stopped by the head safety measure are not included.

D. Trajectory

Since the user study was conducted in a seated setting, the trajectory was fixed at a height of 1.1 m. This enabled a convenient way of tactile interaction since the participants were slightly looking down to the quadrotor (head height $\bar{x} = 1.27\,\text{m}$ ($\sigma = 0.09\,\text{m}$)) and only had to bend their elbow in order to lift their hand to stop the quadrotor by tactile interaction (shoulder height $\bar{x} = 1.04\,\text{m}$ ($\sigma = 0.09\,\text{m}$)).

Before each flight, the quadrotor was placed at the point of origin, where it took off and ascended to the starting point of the trajectory. The flights were then initiated after the participants had verbally confirmed their preparedness. A trajectory was generated from the start position above the origin to the final position at $x = 3\,\text{m}$, right in front of the user, with 6 s duration. The trajectory along the x-coordinate can be seen in Fig. 4; a three-dimensional visualization of just the positions of the trajectory is included in Fig. 3. Thus the quadrotor would decelerate toward the end of the trajectory and would come to a halt right before the user. As an additional safety measure, the distance between the participant's head and the quadrotor was continuously monitored. As soon as it would fall below 0.3 m, the quadrotor was stopped by the flight controller software.

E. Results

Out of a total of 128 conducted flights, there were 27 flights (21.0%) in which the implemented safety measure intervened and prevented the quadrotor from further approaching. In 10 of these cases (three male participants), the quadrotor was not stopped manually, because the participants wanted "to find out what happened" if they would not intervene. In the remaining 17 flights, a stop initiation was detected immediately after the safety stop intervention. Since the quadrotor was already stopping, we cannot determine exactly what the participant-intended stop distance was and thus omit all 27 flights from the numerical evaluation.

1) Approach Stop Proxemics: No matter if the safety measure intervened, 8.1% of the flights stopped in social space, 58.6% in personal space and 33.3% in intimate space. Fig. 5 shows boxplots of all 101 flights, that were stopped by user intervention, for all four directions including all samples color-coded by the stop method. The overall stop distance was $\bar{x} = 0.63\,\text{m}$ ($\sigma = 0.33\,\text{m}$). The foot and hand stop distances were $\bar{x} = 0.73\,\text{m}$ ($\sigma = 0.36\,\text{m}$) and $\bar{x} = 0.47\,\text{m}$ ($\sigma = 0.09\,\text{m}$), respectively. Table I shows the means and standard derivations of the stop distances in each direction by stop method.

2) Approach Stop Method: From 128 conducted flights, 68.0% were stopped by foot switch, 24.2% by hand, and 7.8% flights were not stopped at all. 15 out of 32 users tried to stop the quadrotor by hand at least once. 100.0% of the female participants stopped the quadrotor at least one time by foot and 55.0% at least once by hand. From the male participants, 81.0% stopped the quadrotor at least one time by foot and 53.0% once by hand. 56.3% of the flights approaching from the front were stopped by foot, 37.5% by hand. Flights approaching from the back were stopped in

TABLE I

MEANS AND STANDARD DEVIATIONS OF THE STOP DISTANCES PROVIDED IN METERS FOR EACH DIRECTION.

		Front	Back	Left	Right
Foot	$\bar{x}$	0.80	0.62	0.83	0.71
	σ	0.38	0.37	0.38	0.25
Hand	$\bar{x}$	0.48	0.54	0.48	0.45
	σ	0.10	0.00	0.09	0.06

87.5% by foot and 6.3% by hand. Flights from left and right were stopped by foot in 65.6% and 62.5%, respectively, and by hand in 25.0% and 28.1%, respectively. The proportions of hand-stopped flights to all manually stopped flights in total and for each approach direction can be seen in Table II. In total, the quadrotor was significantly less often stopped by hand than by foot.

From the 15 participants that used their hand to stop the quadrotor from further approaching, eight (53.3%) had stated to have been in contact with a drone before the test. 21.4% (six participants) of the group that stopped the quadrotor by foot stated that they own a service robot or a drone. Of the group that stopped the quadrotor by hand, 40.0% (six participants) stated that they own either a robot or a drone. No statistically relevant correlations could be found between previous experience or ownership of a robot or drone and the stop method or distance. All but one of the group that stopped the quadrotor by hand tapped to the front of the quadrotor's frame. The other participant tapped the quadrotor from the right.

3) Approach Direction: Evaluation of participants' emotions was conducted using a Wilcoxon signed-rank test, which compared initial emotional states with emotional states after each approach direction, self-assessed by the users using the SAM scales. Results show that with the quadrotor approaching from the front, the participants felt a higher level of dominance ($w = 5.0$, $p = 0.002$). The participants arousal was increased when the quadrotor approached from the back ($w = 23.5$, $p = 0.002$) and from the right ($w = 41.0$, $p = 0.037$). There are no statistically significant results for the other directions and emotional states. The means and standard deviations along with the marked statistically significant results from the Wilcoxon test are given in Table III.

The 5-point Likert scale assessing the participants' well-being after every flight comparing one approach direction to the three other directions was evaluated using an independent two-sample t-test. The participants felt less comfortable when the quadrotor was approaching from the back ($t = -2.13$, $p = 0.035$). In addition, the final position of the quadrotor was perceived to be too close to the participants ($t = -3.23$, $p = 0.002$) when approaching from the back after the flight was completed and they were able to turn around to look at the quadrotor.

TABLE II

RESULTS OF A BINOMIAL TEST FOR THE PROPORTION OF HAND STOPS IN MANUALLY STOPPED FLIGHTS OVERALL AND FOR EACH APPROACH DIRECTION. IN THE FLIGHTS APPROACHING FROM THE BACK, FROM THE LEFT SIDE AND OVERALL ACROSS ALL FLIGHTS, THE QUADROTOR WAS STOPPED SIGNIFICANTLY ($p < 0.05$, UNDERLINED) LESS OFTEN BY HAND THAN BY FOOT.

	Front	Back	Left	Right	All
Proportion	0.40	<u>0.07</u>	<u>0.28</u>	0.31	<u>0.26</u>

IV. DISCUSSION

Human-quadrotor proxemics studies are highly dependent on parameters such as the size of the quadrotor, which in turn affects the weight, rotor size, noise and downwash and strongly influences the emotional states of the participants. Obviously, people are affected differently depending on whether a quadrotor is just hanging from the ceiling or its rotor blades are not moving or are protected by a frame. The fact that all the studies mentioned were conducted in different rooms further complicates the comparison between them.

A. Room

The design of the room should definitely correspond to a context of use. In this study, although a seating scenario was aimed for that could occur at home or at work, no correspondingly furnished room was provided. However, since this study was initially concerned only with estimating the distances granted before introducing a specific context, it could be conducted directly in the flight laboratory. Room size and design also influence the emotions of subjects and should be specifically adapted to the context in future studies.

B. Methodology

Next to physical user studies with real hardware, there are several alternatives when it comes to interaction with UAVs. The first that comes to mind is Virtual Reality (VR), especially since the testbed used includes simulation and an OpenGL visualization, which can be ported to VR and AR devices. This is a valuable option to evaluate the participants' interpretation of, e.g., how a quadrotor should move or if they are able to interpret, e.g., the robot's intent. But when evaluating proximity with aerial vehicles, the physical size, the rotor noise and the downwash generated by the rotors have imminent affect on the participants' emotional states. These parameters not being transferrable into virtual environments, basically renders the statistical relevance of a virtually conducted user study useless, no matter if the videos are simulated and rendered or filmed during a real session. The test scenarios should be as realistic as possible.

TABLE III

MEANS AND STANDARD DEVIATIONS OF PARTICIPANT EMOTIONS MEASURED BY 5-POINT LIKERT SCALE SAM QUESTIONNAIRES. INITIAL SURVEYS ARE COMPARED TO POST-FLIGHT SURVEYS USING A WILCOXON SIGNED-RANK TEST; SIGNIFICANT RESULTS ($p < 0.05$) ARE UNDERLINED.

		Initial	Front	Back	Left	Right
Valence	$\bar{x}$	3.91	4.09	3.69	3.94	4.03
	σ	0.80	0.76	1.07	0.83	0.85
Arousal	$\bar{x}$	2.59	2.91	<u>3.28</u>	2.88	<u>2.94</u>
	σ	0.78	1.04	1.04	0.89	0.90
Dominance	$\bar{x}$	2.56	<u>3.12</u>	2.62	2.69	2.81
	σ	0.79	0.78	0.93	0.73	0.81

C. Approach Stop Distance

The average foot and hand stop distances of this user study are depicted in Fig. 1 along with the stop distances of comparable user studies. The average stop distance determined in this study is closest to the participants. Compared to the nearest quadrotor of other studies [13], no increased level of mental stress could be detected during our approach from the front. It stands to reason that both, the closest distance and no detectable level of stress is due to the comparatively very small size of the quadrotor used in this study.

D. Approach Stop Method

The majority of participants interpreted the foot switch as the safe way to stop the quadrotor from further approaching, because they would not want to touch the rotors and cause the quadrotor to crash. Other participants indicated that they chose to stop the quadrotor by hand because it was the more direct method. The lifted hand between oneself and the approaching robot can certainly be interpreted as a form of protection and the raised index finger as dominance. Other participants started to further tap to the quadrotor's frame because they found joy in it.

E. Approach Direction

The increased dominance, as self-assessed by participants, in flights where the quadrotor approached from the front, as well as the decreased comfort and increased arousal with it approaching from the back, is consistent with [17]. The quadrotor could not be observed approaching from the back. This explains the participants' misjudgment of the final stopping distance and their perception that the quadrotor was too close.

F. Skeleton Tracking

We noticed a horizontal offset of $x = 62.4\,\text{mm}$ and $y = -31.1\,\text{mm}$ between the head tracked by the optical pose estimation system and the head skeleton joint measured by the Kinect 2. This horizontal error of 69.6 mm corresponds to the mean error determined in [34], where the Kinect 1 and Kinect 2 skeleton tracking accuracy was compared with a motion capturing system. In a seated position, the mean error of the estimated head joint position ranged from 62–79 mm depending on the angle between the user and the Kinect.

During the user study we only tracked the head position with the Kinect and applied the horizontal offset only to the logged skeleton data for the evaluation of this user study. All measurements in this paper include the horizontal mean error offset. However, during the user study the head safety measure has been determined without the offset and the quadrotor stopped earlier than intended. For this reason 17 flights (that have been interrupted by the participants almost at the same time with the implemented safety measure) could have been used for the numerical distance evaluation. This would have resulted in the quadrotor's average stop distance being even closer to the participants reaching into their intimate space.

G. Quadrotor Pose Estimation

The root-mean-square error (RMSE) of all conducted flights was 49.5 mm and for the x, y and z-coordinates 28.6 mm, 13.9 mm and 37.9 mm, respectively. In some trajectories we noted a negligible instability in the smoothness of the quadrotor's trajectory tracking performance at transitions between cameras. All cameras overlap at edges of their view frustums in order to be able to stereo-calibrate all of them into one reference camera coordinate system. Errors in optical pose estimation are larger toward the edges of the camera image due to lens distortions.

Despite all efforts regarding accurate calibration, camera synchronization and time-dependent averaging of poses, the errors in pose estimation resulted in small peaks in the numerically derived velocity of the quadrotor and caused slight instabilities at camera transitions, marked in Fig. 4. These issues can be fixed and the overall tracking accuracy improved to obtain optimal estimates by adding bundle adjustment [35] as a last step of the camera calibration process.

V. Conclusion & Future Work

This paper presented a user study evaluating distances in tactile HDI. Stopping distances and the participants' inclination to physically interact with a quadrotor were examined. Conducted in a seated fashion with a miniature-sized quadrotor approaching from four directions, this study aimed at future home or workplace scenarios where social drones offer their service to humans. We described and evaluated the conducted experiment and discussed findings. The goal of this work was to examine, wether humans let smaller-scaled UAVs, that have not been modified to add "social" features, into closer distances of their personal space without an increased level of mental stress. Despite the difficulty of comparing different user tests due to many different parameters and methodologies, there is a tendency to see that even mechanical-looking flying robots can fly close enough to humans without detecting an increased level of mental stress when approaching from the front. The fact that almost half of the users were not afraid to use their hands for interaction could not be linked to past experiences with drones or the ownership of robots and encourages further studies of more complex tactile interaction scenarios. The group that voluntarily stopped the quadrotor by tapping its frame even let it cross the boundary into intimate space.

So far we have only evaluated the participants' head positions at the time when the quadrotor came to a halt but have collected all skeleton data throughout all flights. The analysis of this data over time could lead to further insights into the behavior of the participants. Next to further technical improvement of the presented testbed, future work will include user studies that evaluate tactile HDI in greater depth. We are currently working on more interactive scenarios, where different tap directions and forces trigger quadrotor responses in form of situation-dependent trajectories that convey the robot's intent.

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