Integrated Apparatus for Empirical Studies with Embodied Autonomous Social Drones

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ABSTRACT
Current use cases for drones often involve a remote human operator and/or an environment which is inaccessible to humans. Social drones, which we define as autonomous drones that operate in close proximity to human users or bystanders, are distinct from these. The design of social drones,
in terms of both aesthetics and behavior, can involve particular human factors that require further study. Currently, in lieu of empirical studies with autonomous embodied agents, approaches such as Wizard of Oz methods, questionnaires, videos, and/or makeshift mechanisms are often employed to investigate interactions with social drones. For empirical design research using embodied, co-located drones, we have been developing an experimental setup that enables high precision drone control, as well as rich multimodal data collection and analysis, in an integrated fashion. We present this apparatus and its rationale in this paper. Using this setup, we aim to advance our understanding of the psychology and ergonomics of interacting with autonomous social drones through experiments, and extract design implications.

KEYWORDS
Drones, social drones, autonomous drones, empirical studies, experimental setup, motion capture, motion tracking.

INTRODUCTION
In the near future, the drone has the potential to become a paradigm of human-computer interaction in itself [7, 13]. Taking advantage of the drone’s ability to maneuver beyond human reach, many current use cases for drones involve a remote human operator and/or an environment which is inaccessible to humans (see [1, 12, 24]). Conversely, drones may also operate autonomously in close proximity to human users or bystanders (see Figure 1). We use the term social drones to describe this emerging class of applications [7]. Design and development in the context of social drones requires foregrounding human factors, some of which may not have been consequential when a drone is under human control or operating in uninhabited environments.

In previous work, researchers have investigated various aspects of the experience of interacting with social drones, considering the influences of various design dimensions on human experience outcomes (see [7] for a review). However, even though these studies aim to find out more about interaction with embodied autonomous agents, in many of these cases, researchers have not carried out studies using actual autonomous drones. Instead, many studies rely on other techniques: e.g. Wizard of Oz (WoZ) methods, questionnaires, virtual reality (VR), videos, and makeshift mechanisms. In turn, empirical design research with embodied prototypes can yield sophisticated insights into the psychology and ergonomics of interacting with social drones. To be able to conduct such studies, we have designed and implemented an experimental setup for real-time drone control and multimodal
In the context of this paper, we use the term “empirical studies” to denote studies that involve collecting data from (i.e. observing) human participants. In addition to controlled experiments, this includes “interviews, field investigations, contextual inquiries, case studies, field studies, focus groups, think aloud protocols, storytelling, walkthroughs, cultural probes, and so on” [23].

1“According to one definition, empirical means originating in or based on observation or experience” [23]. In the context of this paper, we use the term “empirical studies” to denote studies that involve collecting data from (i.e. observing) human participants. In addition to controlled experiments, this includes “interviews, field investigations, contextual inquiries, case studies, field studies, focus groups, think aloud protocols, storytelling, walkthroughs, cultural probes, and so on” [23].

RELATED WORK AND MOTIVATION

In empirical design studies [23], there must be congruity between study methods and the purpose of the study (e.g. the design stage being addressed). For example, online surveys and various flavors of brainstorming, which rely on participants’ faculties of imagination and articulation, can cater to earlier stages of design characterized by exploration, ideation, and lower-fidelity prototyping. Conversely, experiments with embodied autonomous agents are apt for evaluating design ideas at a higher-fidelity, e.g. capturing correlates of different aspects of the human experience and ergonomics, and efficiently uncovering quantitative design parameters.

Empirical studies with social drones could be said to have emerged as a sub-genre of research literature in more recent years, due to the availability of drone platforms as a consumer commodity. Examining a diverse and representative selection of works from this body of works, we have identified three main strands (see [7] for more detail). The first relates to more general issues of human-drone communication and user experience with social drones [9, 11, 16, 26, 27, 32, 32, 35]. Here, researchers have addressed high-level drone control by co-located humans (as opposed to real-time low-level piloting), conveyance of drone intentions and state through various modalities including motion qualities, and perceptions of comfort and safety in human-drone interactions; aiming to uncover design parameters for intuitive and efficient human-drone communication. A second strand of research deals with use cases involving navigation, assistance, and companionship; employing drones to improve or augment experiences of outdoor wayfinding, exercise and sports spectatorship, and living with sensory disabilities [4, 5, 10, 17, 20, 25, 28]. Finally, social drones have also been utilized to realize novel interaction designs for implementing different flavors of mid-air displays, haptic feedback devices, and interactive tangibles [2, 3, 8, 14, 15, 19, 29–31].

While the aforementioned studies are ultimately about interactions with embodied autonomous drones meant to be co-located with human users or bystanders, only a minority of the published studies utilize actual autonomous drones [16, 18, 25, 33]. In lieu of such high-fidelity prototypes, approaches reported in the literature include online surveys [10, 16, 17, 32], interviews (mostly semi-structured) [3, 5, 9, 11, 16, 20, 28, 31], design studies (including a broad variety of approaches, e.g. ideation sessions, focus groups, and expert critique) [17, 26, 35], WoZ studies [3–5, 9–11, 20, 26–28, 31, 32, 35], and user studies in VR [17].

RATIONALE

As indicated above, empirical studies with social drones is a growing research agenda. However, in the literature so far, studies with fully autonomous drone implementations are not as common as
other kinds of studies. Our experience suggests that implementing drone behaviors and related data collection in a robust manner can require engineering prowess and time, which may pose a high barrier to entry for design researchers. In response to this issue, we aimed to construct and document an apparatus which would be able to collect and respond to highly detailed, multimodal data while implementing precise drone motion control. Based on our learnings from the literature discussed above, and our prior experience with stimulus presentation and data collection apparatus in behavioral experiments, we desired our setup to accomplish the following:

**Drone control.** The drones’ position, orientation, and velocity profile should be controllable, to an appropriate level of precision, through pre-programming movement patterns and responding to events in the scene (e.g. following a human subject or props) in real time. In other words, autonomous flight must be possible, in lieu of a WoZ operator.

**Drone capture.** The setup should allow for recordings, at an appropriate precision, of the position, orientation, and other relevant behavior of drones. For some studies, for example, a video recording may suffice, but this must be synchronized with motion control to facilitate subsequent analysis. Studies requiring high-precision data or efficiently looking for quantitative design parameters (e.g. [21]) can benefit from more precise position tracking.

**Human capture.** It should be possible to record and respond to movements and other behavior of human participants, at reasonable precision. Behavioral measurements may include sophisticated data like motion capture, eye tracking, and physiological measurements (e.g. heart rate, skin conductance, electroencephalography, and electromyography), but may also be due to simpler means—for example, in studies on the psychology of musical perception, researchers have used simple linear potentiometers to acquire real-time, continuous measurements of tension experiences [6, 34]. The overall system must be able to accommodate and synchronize with such instruments.

**Environment capture.** The setup should be able to record and respond to any relevant happenings in the environment, e.g. positions of props or different sensor readings. In the future we expect social drones to surpass human sensory capabilities in many modalities, and communicate with other devices more efficiently [13]. We wish to provide the means for incorporating such novel capabilities.

### OUR APPARATUS

While many simple sensor systems may be used to control and record drone behavior, such solutions often do not provide the flexibility we were aiming for, in that it is not straightforward to track arbitrary configurations of drones, human subjects, and props within the same coordinate system using such systems. Thus, we opted for an optical motion capture as the centerpiece of our control and data collection apparatus.

We utilized a motion capture studio equipped with a Qualisys\(^2\) system, including 12 high-speed marker cameras, 2 spatially calibrated video cameras, and Qualisys Track Manager software (QTM).

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\(^2\)qualisys.com
Figure 3: We used optical motion capture to handle drone motion, human movements, and eye tracking within the same spatial coordinate system. This screenshot taken from the motion capture software shows 6DOF tracking of the drone and the human head, point tracking of the hands and feet, and the gaze vector from the eye tracker.

The system was readily configured for optimum coverage, mainly for biomechanics and animation performance use cases. The total size of the room was $14 \times 10 \times 4$ m, while the motion capture system was able to track a capture volume of approximately $9 \times 8 \times 2$ m in the middle of the room. This motion capture system was configured to track at 100 Hz and used both for data collection and closed-loop control of the drone.

Integration of the motion capture system and the drone was implemented in Python scripts using the open-source cflib\(^3\) and qtm\(^4\) libraries. We have made these scripts available online as open source, under a permissive license\(^5\).

\(^3\)pypi.python.org/pypi/cflib
\(^4\)pypi.python.org/pypi/qtm
\(^5\)github.com/qualisys/crazyflie-resources

We used a Bitcraze\(^6\) Crazyflie 2.0 drones, with chassis dimensions of approximately $10 \times 10 \times 2$ cm. Four spherical infrared-reflective motion capture markers, $9.5$ mm in diameter, were attached to the drone using a “MoCap marker deck” fabricated from the same printed circuit board material as the frame of the drone. QTM was configured to track this marker set in 6DOF as a “rigid body.” (As an implementation detail, we note that proper 6DOF tracking requires the markers to be attached asymmetrically.)

We incorporated a Tobii Pro\(^7\) Glasses 2 wearable eye tracker into our setup. This device was equipped with 6 motion capture markers of the same size as on the drone, again configured for 6DOF tracking. In QTM, gaze vectors for both eyes were overlaid onto the motion capture data (see Figure 3).

\(^6\)bitcraze.io
\(^7\)tobiipro.com
Along with head and gaze tracking, attaching other markers to participants can provide information on participants’ reflexive reactions to drone behaviors, and may be used to enable gesture control or other responsive drone behaviors. In addition to motion tracking, we incorporated a wired trigger button used to obtain binary input and record it with precise timing. This button was connected directly to the motion capture system on a hardware level to minimize signal latency.

Finally, we considered safety measures. Our experience has been that our drone is small and lightweight enough to be incapable of damaging clothes or skin upon contact. To protect participants’ hair from possible contact with the drone’s propellers, we procured a hair net. Eye protection was provided by a clear plastic attachment fitted onto the eye tracker.

EXPERIENCES, LIMITATIONS AND FUTURE WORK

A subset of the apparatus we propose in this paper has been used to implement a technical demonstration that explores how a small drone can be used to facilitate meditative movement exercises [22]. We also note that fundamentally similar equipment has been used by other researchers to prototype and demonstrate free-flying tangible user interfaces [15, 29].

Our preliminary work with the apparatus has revealed a set of improvement possibilities. So far, we have only been using the Crazyflie drones, which are smaller compared to drones used in much of previous work, and thereby have limited use cases. Future work can address developing the software to integrate different drones in the setup, and identifying different use cases where the smaller drone is more appropriate. Furthermore, while the particular motion capture system we had at our disposal has advantages in terms of precision and flexibility, such systems are costly. Systems with different cost/performance characteristics can be substituted in its place, but the software will need to be reworked—a more general software framework to interface motion tracking, drone control, and other systems can be explored in future work. Lastly, future work can also investigate adding further data acquisition capabilities. For example, sensors for recording electrodermal activity (a.k.a. skin conductance or galvanic skin response) or other physiological measurements could be introduced.

CONCLUSION

In this paper, we have presented our design and implementation of an experimental apparatus for empirical research on human factors in social drones. This apparatus supports integrated multimodal data acquisition at high spatial and temporal resolution, and real-time closed-loop drone control with high precision. Here, along with details of the setup itself, we reported on its design rationale and how various aspects of it relate to previous work. Through this report, we have aimed to share a description of our apparatus at some detail, in order to serve as a resource for other researchers looking to undertake similar studies. We would also like to open up our approach to critique; and we
invite others in the field to provide feedback and share experiences regarding how future work on the apparatus can better serve the community.

REFERENCES


