The Design of Social Drones

A Review of Studies on Autonomous Flyers in Inhabited Environments

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ABSTRACT

The design space of social drones, where autonomous flyers operate in close proximity to human users or bystanders, is distinct from use cases involving a remote human operator and/or an uninhabited environment; and warrants foregrounding human-centered design concerns. Recently, research on social drones has followed a trend of rapid growth. This paper consolidates the current state of the art in human-centered design knowledge about social drones through a review of relevant studies, scaffolded by a descriptive framework of design knowledge creation. Our analysis identified three high-level themes that sketch out knowledge clusters in the literature, and twelve design concerns which unpack how various dimensions of drone aesthetics and behavior relate to pertinent human responses. These results have the potential to inform and expedite future research and practice, by supporting readers in defining and situating their future contributions. The materials and results of our analysis are also published in an open online repository that intends to serve as a living hub for a community of researchers and designers working with social drones.

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CCS CONCEPTS

• **Human-centered computing** → **Interaction design**; **Empirical studies in interaction design**;

KEYWORDS

Drones, social drones, drone design, empirical studies, user studies, design knowledge, human-drone interaction, autonomous agents

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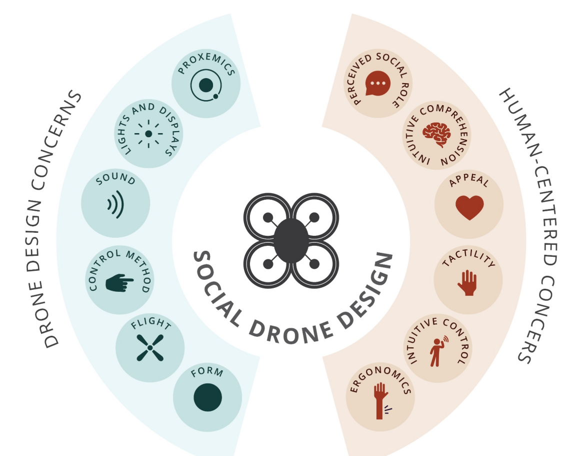

Figure 1: Our analysis of the literature reveals high-level categories that describe the design space for social drones.

1 INTRODUCTION

Autonomous flying drones have the potential to be ubiquitous in the future, possibly as a major HCI paradigm: "flying user interfaces" may soon be a common research agenda [23] and design direction for commercial products [69]. Already, drones are deployed in research and applications across a diverse array of domains[1]; while arguably, "human-drone interaction has become a special sub-field of human-robot interaction" [23].

In practice, most current drone applications are motivated by maneuverability, with a remote human pilot using a drone to inspect or manipulate subjects in an environment not easily accessible to humans. Conversely, there is an emerging class of applications where fully autonomous drones operate in spaces populated by human users or bystanders. We propose the term *social drones* to describe these applications (see Figure 2): since some form of social interaction is unavoidable when two or more living agents occupy the same environment, we submit that an autonomous embodied agent in an inhabited space can be similarly described as *social*. As such, the design of social drones and their behavior warrants foregrounding social and human factors.

In recent years, enabled and motivated by the commodification of drones, researchers have conducted many empirical studies to produce human-centered design knowledge on social drones. This knowledge, borne from a wide-ranging continuum of engineering and design research, explores numerous factors such as acceptability [17, 35, 54, 76], acknowledgement [31], anthropomorphism [13, 20, 35, 47], attention [17, 41, 47, 54], communication [17, 54, 63], companionship [35, 47], control [13, 20, 47], emotional expression [20, 35], enjoyment [35, 41, 47, 54], safety [13, 47], and task performance [6, 17, 41, 63]; which are linked to design decisions including those related to motion and proximity [13, 17, 31, 35, 47, 63, 76], form (including size, color, facial features, etc.) [35, 47], projected graphics [41], sound [6, 76], and the cultural context where the application is deployed [20, 76]. This body of knowledge builds upon a diverse variety of commitments and approaches, which presents challenges for researchers, resulting, for example, in works that may partially repeat each other. Similarly, for designers, extracting congruent, concrete, and practical design knowledge from this material may be difficult. The need for a resource that consolidates human-centered design knowledge on social drones is thereby motivated. Intending to address this need, this paper contributes a report on the state of the art in empirical design research on social drones, aiming to inform and expedite future research and practice.

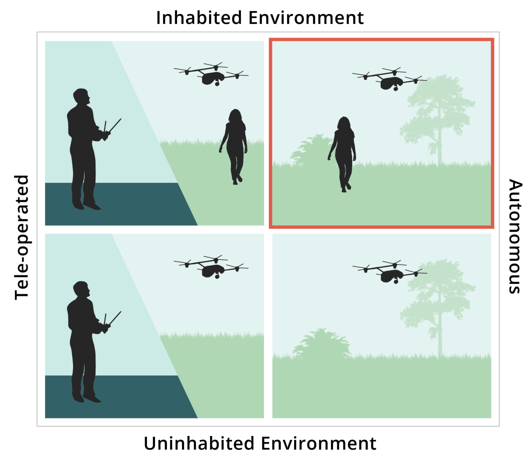

Figure 2: We use the term *social drones* to describe applications where an autonomous drone operates in an environment inhabited by human users or bystanders, as depicted on the top right quadrant.

The rest of the paper is organized as follows: We first describe the methodology we followed in reviewing and presenting the current state of the art on social drones, including a framework formulated to enable end-to-end, post-hoc characterizations of empirical design studies. This preliminary framework has the potential to be further developed and applied in other domains, and thus emerges as a minor contribution of this work. Based on this, we then present an overview of research on social drones focusing on the questions and applications that have driven research, as well as the research methods employed. Subsequently we provide a consolidated account of design knowledge resulting from this research, highlighting collectively salient findings and suggesting directions for future work. We conclude after discussing emergent issues related to both our methodology and the subject matter.

In the process of producing this paper, we have also created an open online repository of design knowledge on social drones, comprising prospectuses that summarize a corpus of research papers, as well as consolidated and comparative representations of design knowledge on the topic[2]. This repository intends to serve as a living hub for a community of researchers and designers working with social drones by providing affordances for input and discussion. We submit this repository as a distinct contribution to the community.

[1]Examples include construction and structural inspection [30, 66, 71], military and search-and-rescue operations [1, 34, 61], space exploration [22, 46], logistics [19, 72], accessibility [6], smart homes [35], sports and exercise [47, 54], and tangible user interfaces [25, 39, 40].

[2]github.com/socialdrones/designreview/

2 METHOD

We began our effort in consolidating human-centered design knowledge on social drones by constructing a corpus of research papers, following an approach based on literature reviews previously published at CHI [18, 33]. We first curated relevant papers from search results for the terms "social drones, human drone interaction, drone design" in the ACM Digital Library[3]. The searches were done between August 6-17, 2018. Each paper from the results was examined and added to our corpus based on 2 criteria:

(1) Does the paper relate to the case of an autonomous drone operating in an environment populated by humans? Based on this, for example, works dealing with piloting—i.e. real-time low-level motion control—in lieu of autonomous flight were excluded (e.g. [21, 29, 45, 53]).
(2) Does the paper report on studies where information (including opinions) was collected from human subjects? This led, for example, to the exclusion of technical research that does not cover human factors (e.g. [11, 44, 62, 68]), and design proposals without human-centered studies (e.g. [37, 42, 43, 73]).

This resulted in a selection of 31 papers, and 7 more were discovered through reference crawling, resulting in a corpus of 38 papers. Thereafter, we also performed searches using the same keywords in Google Scholar and the IEEE Xplore Digital Library, but did not come across additional relevant results. The final corpus comprised papers published between 2011 and 2018 in 17 different venues (see Figure 3).

Based on preliminary readings of these papers, we developed a set of questions that would enable us to summarize the studies presented, in order to subsequently consolidate and compare findings. These questions were:

(1) What are the core research questions investigated through empirical studies?
(2) What are the study methods used?
(3) What kind of drone or other apparatus was used?
(4) What results have been obtained from the studies?
(5) How do the results inform design; i.e. what design implications, lessons, or guidelines have been derived from the results?

Each paper in the corpus was summarized in the form of a "prospectus" with answers to the questions above. For some works of highly exploratory and qualitative nature, questions 4 and 5 were merged into one. These prospectuses are available for viewing online in an open repository that also provides affordances for contributions in the form of additions, edits and discussion[4].

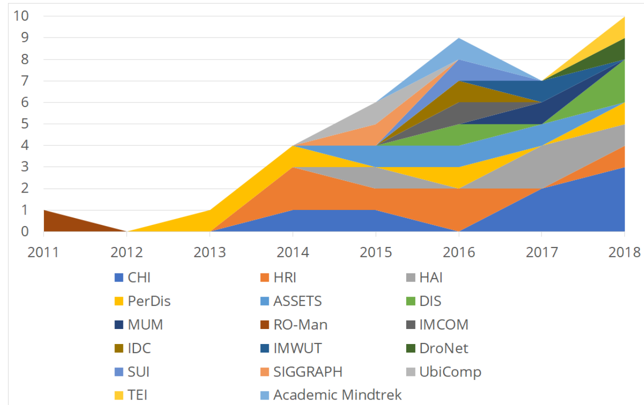

Figure 3: The research agenda of social drones has been on the rise in recent years: the chart depicts the numbers of papers in our corpus for each year, and where they have been published.

Subsequently, to consolidate, compare, and present findings and implications from these empirical studies, we devised a more structured approach. This was based on a framework that describes the process of knowledge creation for drone design through empirical studies as a sequence of 3 steps, involving: (1) the identification of a driving theme, question, or use case; (2) the selection of empirical methods, to study the aforementioned; and (3) arrival at findings that expose how concerns related to certain human responses and/or desiderata relate to particular concerns in product and interaction design.

In using the term *design knowledge*, we refer to the final step of the above process; denoting associations between what we labeled *drone design concerns* (DDCs) and *human-centered concerns* (HCCs). Thus, here we conceptualize design knowledge as associations between human responses to, or desiderata for, particular design features. We note: we do not suggest that empirical design studies in reality do or should conform strictly to such a clearly structured, sequential process; nor do we suggest that studies should always be driven by precise goals and operationalizations of what concerns and associations are to be investigated. Rather, our framework means to be descriptive rather than prescriptive, enabling post hoc characterizations of the goals, methods, and results of such studies. Indeed, many studies in our corpus are highly exploratory in nature, and even for hypothesis-driven experiments, emergent findings are often significant.

[3]The ACM Digital Library has been previously used as the main or only resource for HCI research literature in many peer-reviewed papers [18, 33, 52, 60, 75].

[4]github.com/socialdrones/designreview/tree/master/prospectuses

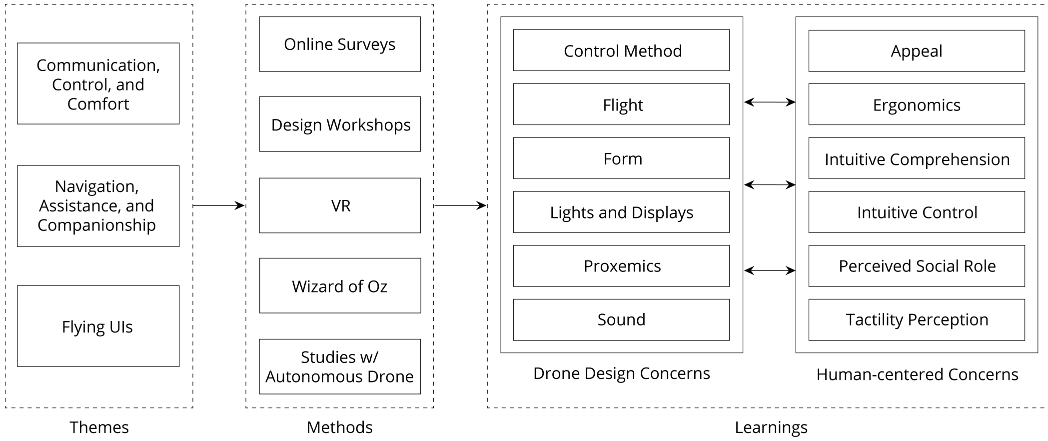

Figure 4: A diagram of the process of design knowledge creation on social drones, including the categories for themes, methods, and concerns that have emerged from our corpus.

The next two sections in this paper review our corpus of empirical design studies on social drones through the lens of this framework. Figure 4 presents a diagram of the framework, which also includes themes, methods, and concerns that emerged from our corpus. These concerns are also illustrated on Figure 1.

3 DESIGNING SOCIAL DRONES: METHODS AND THEMES

The methods used in our corpus of papers to generate design knowledge on social drones can be clustered into five categories, mainly based on how designs or topics under investigation are presented to study participants. (1) *Online surveys* have been used to present videos, pictures, or descriptions of drone behaviors to participants, and to collect responses as multiple-choice answers and/or free text. Here, participants do not encounter the researchers or a drone in person. (2) *Design workshops* comprise a broad variety of formative design studies, including ideation sessions, focus groups, in-depth interviews, and expert critiques. Participants meet researchers in person, but do not encounter drones that implement any designs under investigation. However, they may be presented with a generic drone that does not implement a specific design, as well as more abstract representations of design ideas. (3) *Virtual reality (VR) studies* present interaction designs to participants in VR, without using embodied prototypes. (4) *Wizard of Oz (WoZ) studies* comprise in-the-wild or lab presentation of designs via an embodied, co-located drone under real-time manual control of an operator, rather than algorithmic. Finally, (5) *user studies with autonomous drones* present higher-fidelity prototypes with drones flying autonomously, under algorithmic control (barring the possibility of a manual intervention in an emergency), where the algorithm may be receiving input from sensors, or executing pre-defined behaviors. Each work included in our corpus applies one or more of these methods to study how elements of designed drone aesthetics and/or behavior relate to elements of human experience with the design; where both drone- and human-related concerns under investigation may be intentionally selected or emergent.

It is noteworthy that while the studies covered almost exclusively focus on autonomous drone design, the majority (27 out of 38) have been done without an actual autonomous drone, and 8 papers report on design studies that do not involve an embodied drone at all. Here we simultaneously acknowledge the contributions of diverse approaches to design knowledge predicated on future technologies, and point out a motivation for future work on prototyping and development tools for design researchers working with autonomous drone behavior.

One form of analysis we found relevant in consolidating the knowledge in our corpus is a high-level clustering based on the themes that characterize each paper, which mainly relate to the driving research questions and use cases. From this perspective, three overarching themes have emerged. Below, we unpack these themes, aiming to expedite future work by sketching out knowledge clusters which can assist researchers in defining and situating their contributions of design knowledge for social drones. Almost every paper in our corpus fits neatly in one of the three themes, as indicated on Table 1; minor ambiguities were resolved through discussions between authors, and indicated below.

Table 1: An overview of themes, methods, and findings identified in our corpus of empirical design research papers on social drones.

Reference		Themes			Methods					HCCs						DDCs					
		CCC	NSC	FUI	Online Survey	Design Workshop	User Study in VR	Wizard of Oz Study	Study w/ Auton. Drones	Appeal	Ergonomics	Intuitive Comprehension	Intuitive Control	Perceived Social Role	Tactility Perception	Control Methods	Flight	Form	Lights and Displays	Proxemics	Sound
[48]	Ng and Sharlin 2011	●	-	-	-	●	-	●	-	●	●	-	-	●	-	●	-	-	-	-	-
[57]	Scheible et al. 2013	-	-	●	-	-	-	●	-	●	-	-	-	-	-	-	○	-	●	○	○
[5]	Arroyo et al. 2014	●	-	-	-	-	-	-	●	●	-	●	-	-	-	-	●	●	●	-	●
[58]	Schneegass et al. 2014a	-	-	●	-	-	-	●	-	●	●	-	-	-	-	-	●	-	●	○	-
[59]	Schneegass et al. 2014b	-	-	●	-	-	-	●	-	●	●	-	-	-	-	-	●	-	●	○	-
[63]	Szafir, Mutlu, and Fong 2014	●	-	-	●	-	-	-	●	●	-	●	-	-	-	-	●	-	-	-	-
[6]	Avila, Funk, and Henze 2015	-	●	-	-	-	-	●	-	-	●	-	-	-	-	-	-	○	-	○	●
[13]	Cauchard et al. 2015	●	-	-	-	-	-	●	-	●	●	-	●	-	-	●	-	-	-	○	○
[16]	Chen, Liu, and Yu 2015	●	-	-	-	-	-	-	-	○	-	-	●	-	-	●	-	-	-	-	-
[47]	Mueller and Muirhead 2015	-	●	-	-	-	-	-	●	●	●	●	-	-	-	-	●	-	-	○	-
[50]	Obaid et al. 2015	●	-	-	●	-	-	-	-	●	-	●	-	-	-	-	○	-	●	-	●
[64]	Szafir, Mutlu, and Fong 2015	●	-	-	-	-	-	-	●	-	-	●	-	-	-	-	-	-	●	-	-
[4]	Al-Zayer et al. 2016	-	●	-	-	-	-	●	-	●	●	-	-	-	-	-	-	-	-	●	●
[14]	Cauchard et al. 2016	●	-	-	-	-	-	●	-	○	-	●	-	○	-	-	●	-	-	-	-
[28]	Hieida et al. 2016	●	-	-	-	●	-	-	-	-	-	●	-	-	-	-	●	-	-	-	-
[32]	Jones et al. 2016	-	-	●	-	-	-	-	●	●	●	-	-	-	-	○	○	○	-	○	○
[37]	Kim, Kim, and Kim 2016	-	●	-	-	-	-	-	-	●	-	●	●	●	-	●	●	-	-	-	-
[49]	Obaid et al. 2016	●	-	-	-	-	-	●	-	-	●	-	●	-	-	●	-	-	-	-	-
[56]	Scheible and Funk 2016	-	-	●	-	-	-	●	-	●	-	-	-	-	-	-	-	-	●	-	-
[74]	Yamaguchi et al. 2016	-	-	●	-	-	-	●	-	-	●	-	-	-	-	-	●	-	-	-	-
[78]	Zwaan and Barakova 2016	-	●	-	-	-	-	●	-	●	●	○	-	-	●	-	●	○	-	○	-
[3]	Abtahi et al. 2017	●	-	-	-	-	-	●	-	●	●	-	●	-	●	●	-	●	-	●	-
[7]	Avila Soto et al. 2017	-	●	-	-	-	-	●	-	●	●	●	-	-	-	-	●	-	-	○	●
[15]	Chang, Chundury, and Chetty 2017	●	-	-	-	-	-	●	●	-	-	-	-	-	-	●	●	●	●	●	●
[17]	Colley et al. 2017	-	●	-	●	-	-	●	-	●	-	●	-	-	-	-	●	-	-	●	○
[20]	E et al. 2017	●	-	-	-	-	-	●	-	●	●	-	●	-	-	●	-	-	-	●	-
[35]	Karjalainen 2017	-	●	-	●	●	●	-	-	●	-	-	-	●	-	●	-	●	●	●	-
[76]	Yeh et al. 2017	●	-	-	-	●	-	●	-	●	-	-	-	-	-	●	●	●	●	●	●
[12]	Brock et al. 2018	-	●	-	-	●	-	-	●	●	●	-	-	-	-	●	-	-	●	-	-
[27]	Han and Bae 2018	●	-	-	-	-	-	-	-	●	-	-	-	-	-	-	●	●	-	●	-
[31]	Jensen, Hansen, and Knoche 2018	●	-	-	●	-	-	-	●	●	-	●	-	-	-	-	●	-	-	●	-
[36]	Khamis et al. 2018	-	-	●	-	-	-	-	-	●	●	-	-	-	-	●	●	●	-	○	-
[38]	Kim and Landay 2018	-	-	●	-	-	-	-	●	●	-	●	-	-	-	●	●	-	-	-	-
[39]	Knierim et al. 2018a	-	-	●	-	-	-	-	●	●	●	-	-	-	●	●	-	●	●	-	○
[41]	Knierim et al. 2018b	-	●	-	-	-	-	●	-	●	●	●	-	-	-	-	○	-	●	-	○
[65]	Tan, Lee, and Gao 2018	-	●	-	-	-	-	●	-	●	-	-	-	●	-	-	●	●	-	-	-
[67]	Uchidiuno, Weisz, and Manweller 2018	●	-	-	●	-	-	-	-	●	-	-	-	-	-	●	●	-	●	●	-
[70]	Walker et al. 2018	●	-	-	-	-	-	-	●	●	●	●	●	●	-	●	-	-	●	-	○

-: not relevant; ●: relevant; ○: relevant implicitly, partially, or in an emergent fashion.
CCC: Communication, Control, and Comfort; NAC: Navigation, Assistance, and Companionship;
FUI: Flying User Interfaces.
HCC: Human-centered Concern; DDC: Drone Design Concern.

Communication, Control, and Comfort

This cluster of research deals with interaction and user experience on a comparatively generic level, focusing on questions around intuitive high-level input, i.e. issuing commands to control drone behavior; intuitive output, i.e. drones communicating their intentions and internal state to humans; and on revealing design parameters that affect human comfort and trust. Communication, control, and comfort is a major theme in our corpus, represented by 17 out of 38 papers.

About half of these works are concerned with the elicitation and/or evaluation of control schemes or command repertoires for issuing high-level commands to drones in intuitive or natural fashions. Typical examples are studies on interaction designs for gesture- and voice-based drone control. [16, 48, 51]. An oft-cited study by Cauchard et al. (2015) investigating "natural" user preferences in how to issue various commands to a co-located drone [13]—as well as its later adaptations by E et al. (2017) to investigate cross-cultural variations [20] and by Abtahi et al. (2017) to investigate tactile interactions [3]—fall in this category; as does the more comprehensive investigation of an end-to-end system prototype for robot command in augmented reality by Walker et al. (2018) [70]. *Control methods* emerge as a major design element investigated in these studies; and analyses concentrate on human responses around the intuitiveness of said control schemes, often quantified through agreement scores between participants. The *ergonomics* and *appeal* of interaction designs are also common concerns.

Other works in this group have investigated how internal states or future actions (i.e. intent) of a drone may be communicated to users or bystanders intuitively through behaviors and design features including flight trajectories and on-board lights or displays. For example, Szafir et al.'s 2014 studies have evaluated film- and animation-inspired motion manipulations (easing, arcing, and circling in "anticipation") in terms of how they could be used to modulate perceptions of product appeal, naturalness, and safety [63]. This was followed up by another work by the same authors [64] proposing various animated lighting designs on a drone as a medium to communicate intent regarding flight direction. Also belonging to this cluster are studies on how "emotional states" can be encoded in flight characteristics (speed, height, reaction time, and special movements such as wobbles and flips) [14, 28]; and Jensen et al.'s (2018) work on designing flight behaviors to communicate "acknowledgement" through a suite of three empirical studies [31]. These studies prominently relate design choices around *flight* and *proxemics*, along with *lights and displays*, to human responses pertinent to *intuitive comprehension* of drone behaviors.

In the majority of the aforementioned studies, in addition to the cognitive and physical ergonomics of various designs for control and communication, feelings of safety and comfort have received significant attention. As such, these concerns have been clustered into this one theme. In addition, included here are Chang et al. (2017) and Uchidiuno et al.'s (2018) reports on a battery of innovative studies focusing on perceptions of privacy and security around co-located drones as a primary concern [15, 67]; and works dedicated to exploring human-drone proxemics [27, 76].

Use Cases: Navigation, Assistance, and Companionship

This cluster, covering around 30% of our corpus, investigates use cases where drones are to provide assistance or experiential augmentation in an existing daily effort or context. While there are works here that are significantly different from each other in terms of subjects and approaches, they exist on a continuum of use cases which would be difficult to delineate otherwise.

Drones as navigational aids that replace or augment existing maps and signage is a use case occurring often in this cluster. A variety of concepts have been proposed and evaluated for this purpose, including projecting maps [12] and navigational cues [41] onto the walking environment to support pedestrian navigation, and communicating directions via flight "gestures" executed in air [17]. In addition to targeting typical populations, much work on drone-assisted navigation proposes designs intended to assist the visually impaired in outdoor wayfinding, indoor mobility in crowded environments, and object localization [4, 6, 7].

Sports and exercise are other prominent topics here. Drone-based prototypes have been proposed to augment experiences in jogging, for both the seeing [47] and the blind [4]; racing, for both spectators and competitors [54]; and boxing [78]. Finally, included here are studies of primarily exploratory nature that pertain to applications for drones as private companions or fulfilling socially motivated roles in public spaces: Obaid et al. (2015) have investigated interaction designs for drone encounters aiming to facilitate the maintenance of cleanliness in public spaces [50]; while Karjalainen et al. (2017) have elicited and evaluated potential roles for drones as domestic companions through a suite of studies including one in a VR environment [35]. Many of these studies are exploratory, aiming to unpack the *appeal* of various design concepts (and other aspects of the user experience) through formative prototypes.

Use Cases: Flying User Interfaces

This final cluster includes work on novel interaction concepts built upon free-flying autonomous drones as a core enabling technology.

Many papers in this group report on concepts where drones are used to carry displays for text, images, and video. Many of these concepts have been prototyped and evaluated through WoZ methods with a human pilot, but the ultimate vision almost always involves autonomous flight. Experiments have been done with a variety of display techniques including rendering content on walls with drone-mounted projectors [57], directly mounting tablets onto drones [58, 59], and having drones carry both projectors and target surfaces [56]. These studies have produced knowledge on the *appeal* and *ergonomics* (including legibility) of such interaction designs across contexts and conditions.

Another prominent concept in this category is the use of drones as airborne tangibles that can be touched, grabbed and manipulated, or be otherwise utilized as haptic interfaces[5] towards realizing direct manipulation interfaces involving

[5]Haptic affordances have also been the subject of studies related to control and comfort (e.g. [3]), but works falling in this final category are differentiated by their focus of specific haptic interaction concepts, rather than comfort around tangible drones on a more generic level.

drones [39] as well as enabling flexible haptic feedback in VR [74]. The focus in these studies is mostly on qualitatively understanding how these concepts can *appeal* to users, as well as validating whether or not people are able to perform tasks with them as intended. We must also note a number of research publications that were not included in our corpus, where similar designs are proposed—these were excluded since they do not report on human-centered empirical studies (e.g. [2, 10, 24, 25, 55]).

Finally, experiments with rather unique interaction concepts are clustered here. For example, Jones et al. (2016) have prototyped a drone-based system to facilitate remote collaboration between a person on the "field" and another one headquartered at a workstation [32]; Khamis et al. (2018) have proposed a drone-based system for unencumbered eye tracking [36]; and Kim et al. (2018) have reported on a dance performance involving human-drone interactions [38].

4 FINDINGS

As detailed before, we have analyzed the results and implications from the studies in our corpus through unpacking how they address various concerns related to design elements and the human responses they evoke. From this literature, we have identified 6 *drone design concerns* (DDCs) and 6 *human-centered concerns* (HCCs), which allowed us to consolidate and compare findings across studies. These were defined so that a high degree of orthogonality was maintained between categories, along with inclusive coverage of the design knowledge in the literature.

The below presentation of this analysis comes with two caveats. First, the knowledge to be covered is quite voluminous. Second, we recognize that our present clustering is not the only one possible; particularly since the relevance and delineation of various concerns may change over time, with the evolution of related technologies and how they integrate into human lives. As such, to present this analysis comprehensively and enable its evolution with time and input from research and design communities, we have created an open online repository of design knowledge for social drones. We invite readers to view the entire range of findings online; and below, we present salient highlights in prose. Here, we focus on heuristics based on design knowledge where strong associations between HCCs and design concerns have been found, or agreements or disagreements have been identified between multiple studies. For concision, the highlights below are clustered based on what HCCs they address, and each cluster is prefaced with an unpacking of what exactly each HCC is about, in the form of questions. Where relevant, we expose directions for future work. The converse of this analysis, i.e. knowledge on how each DDC influences human factors, is offered in the online repository; though here, prior to presenting said highlights, we must describe what meanings, intentions, questions, and design spaces are associated with each of our 6 DDCs in summary:

- Investigations concerned with *control methods* assess designs for issuing commands to drones. Since our scope is delimited by autonomous, rather than teleoperated drones, these methods often pertain to schemes for giving high-level commands (e.g. "take off" or "follow me") rather than piloting the drone in real time. This concern covers various formative, summative, and comparative investigations of a variety of control modalities including voice, gesture, and external devices; and may draw on various design stages and levels of fidelity, ranging from generic and exploratory to performance with particular implementations.
- *Flight* refers to interaction designs that deal with a drone's movements and stance. Studies concerned with flight often introduce designs for motion patterns or styles informed by theory to participants, and investigate how they are perceived on various cognitive and visceral levels.
- *Form* comprises all aspects of the visual appearance of a drone, including size, shape, color, and appendages[6].
- Drone-mounted *light and displays* across a continuum of resolution characteristics have been studied as a communication medium. Works looking at how these can efficiently serve as media communicating internal system states or other messages, as well as the legibility and ergonomics or reading them, are related to this concern.
- *Proxemics* is study of proximity as a channel of communication, interaction, and cultural elaboration[7]. From the literature, proxemics emerges as a concern that is distinct from flight, with some studies focusing exclusively on its influence on human experience outcomes.
- *Sound* is related to sound designs (including voice) that may be reproduced on a drone with on-board speakers, as well as the noises produced by a drone's spinning propellers and flight motions.

The above DDCs represent a high-level clustering of various design decisions pertinent to social drones; while HCCs, as explained below, relate to aspects of the human experience with social drone designs that are modulated by these decisions.

[6]No studies in our corpus have implemented moving drone appendages that can interact with the external world in practice; and as abstract design ideas (as in [35]), we cluster these into the DDC *form*.

[7]The term proxemics was defined by the cultural anthropologist Edward T. Hall as "the interrelated observations and theories of man's use of space as a specialized elaboration of culture" in his 1966 book *The Hidden Dimension* [26].

Appeal

Are people willing to accept, acquire, and/or use a drone or drones, as designed, for the purpose under investigation? Do people feel psychologically comfortable and safe in interacting with the drone(s) or simply cohabiting the same environment? Do they have confidence that the drone will not inflict damage or otherwise misbehave?

Human acceptance of and comfort around drones, which are often linked to perceptions of safety and stability, are significant and delicate design considerations. Many of the drivers of comfort and acceptance around drones have their roots in physiological and evolutionary mechanisms, and exhibit significant variance between people and cultures [4, 27, 31, 32, 50, 65], which product designs must respect. To begin with, many studies indicate that when it comes to drones meant for close encounters with humans, the smaller the design, the better [13, 15, 76]. Further, research agrees that noise and airflow originating from propellers can very easily become bothersome [13, 15, 17, 32, 39]. Even for use cases requiring high visibility or carrying capacity, size and noise are important considerations, for the comfort of bystanders.

The external appearance of a drone, naturally, contributes to its appeal [35, 56]. More interestingly, studies have also considered the effect of flight characteristics on psychological ease, arriving at a rich multitude of heuristics and design suggestions. On a high level, it can be said that flight characteristics of co-located drones correlate strongly with human comfort. Random, "mechanical" instabilities and a lack of compensation for wind perturbations are highly undesirable [59]; while intentful design of drone motions can be leveraged to easily invoke positive sentiment [37, 63], as well as perceptions of threat and aggression [31]. Specifically, smooth and stable motions (e.g. "easing" effects) correlate with positive sentiment, and abrupt motions with discomfort. While well-designed motion characteristics seem to be very effective in inspiring particular human reactions, we note from the literature as well as personal experience that their implementation often requires engineering prowess, and future work on higher-level programming and design tools for drone motion is well-motivated.

Beyond notions of aesthetics and biologically-driven comfort, significant design issues with drones revolve around social acceptance and privacy concerns. While many study participants were able to comfortably interact with social drones as individuals, many concerns were noted over how drones can integrate in social and public settings across use cases [7, 15, 32, 36, 50, 65]. Worries include the feeling of being "watched" by a sensor-loaded drone; perturbations to human socialization by drones in the environment; as well as ones around dignity and authority, e.g. people being uncomfortable about being "told what to do by a drone" in cases where drones are intended to motivate certain behaviors [50]. These works conclude with suggestions around indicating the presence, internal state (e.g. recording, following, acknowledging), and likely behavior of drones through signage and cues on drones [15, 31, 32, 36, 65] and in environments [15, 50]; which can be explored in detail via future work.

Ergonomics

Are people physically comfortable in interacting with the drone(s) using the proposed interaction design(s)?

Ergonomics in the context of interactive drones has been most relevant for gesture-based control schemes, drone-based tangibles, and in cases where users are supposed to direct their attention or whole body to follow a drone. The literature suggests various heuristics for each of these contexts.

For gesture-based control schemes, it is suggested that props can easily become cumbersome and are to be avoided if possible; and large gestures quickly lead to "gorilla arm"-type exhaustion [48]. Similarly, studies with compact flying tangibles affording "push" and "drag" interactions also report that a modest interaction space, roughly 1 m in each direction, and positioned between elbow and chest height, provides for favorable ergonomics. These studies have been executed with WoZ methods, and practical investigations of drone-mounted gesture recognition capabilities may be of interest for future work.

For cases where a drone is meant to be followed with the gaze, studies suggest caution against extensive movement, especially of the user. Experiments with drone-mounted displays have shown that legibility can be good when both the observer and the drone are static, and reasonable when the drone moves; but content can become illegible in cases where the user's movement exceeds a slow walking speed [58, 59]. Maintaining interaction with a drone-mounted eye tracker has also been reported to become similarly challenging for a moving human [36]. Conversely, such issues have not been reported with displays based on drone-mounted projection. Collectively, these findings suggest that stability of the user and the medium can both be critical for drone-based displays.

Some studies, particularly for assistive technologies for the blind, have involved using propeller noise to localize a drone [4, 6, 7]. The results here are mixed, with initial explorations producing promising results, while more rigorous studies with greater numbers of participants and more sophisticated methodology revealing drawbacks in terms of both users' confidence in the technology and its performance in noisy environments. Intentional design of both mechanical and speaker-reproduced sounds for these applications has been left for future work.

Intuitive Comprehension

To what degree are people able to interpret intentions or messages that the drone is trying to convey via the interaction design under investigation, without extensive documentation or explanation?

Comprehension of a drone's internal state, future actions, and task instructions by humans can be motivated by comfort, safety, or task performance considerations in many contexts. To this end, researchers have primarily investigated the use of flight behaviors [14, 17, 28, 31, 63], as well as lighting designs [64]. For many such applications, researchers note that it pays off to have an external design with a discernible "front," and to take care in designing flight gesture repertoires that are distinct from regular flight motions. Further, the smoothness of motions is noted to be correlated with intuitive comprehension of drone intent [63]. Drone motion has also been successfully leveraged for the potentially more cognitively demanding purpose of communicating navigational instructions, but some flight gestures (such as "straight ahead") in this case were also associated with discomfort due to abruptness [17]. In all cases, researchers note that there is a limitation in how fine-grained such interpretations of intention, state, and instruction from drone motion and abstract lighting designs can be, and suggest that precise communication is best documented explicitly or designed involving other modalities [70].

Intuitive Control

To what degree are people able to intuitively control the drone via the interaction design under investigation, without extensive documentation or explanation? What kinds of interaction designs would be conducive to such intuitive control?

While smartphone applications and joystick-based controllers are common in drone piloting, many studies in our corpus have focused on designing and evaluating control schemes based on gesture and voice [13, 16, 48, 49]. Furthermore, in exploratory studies, gesture and voice have emerged as the preferred modes of communicating with social drones [35]. Preferences between voice and gesture appear to be dependent on context, as well as familiarity; with participants in outdoor and public contexts feeling initial discomfort with talking to drones and relying on gesture before becoming comfortable with voice interactions over the course of studies; and participants in private environments expressing a preference for voice interaction. However, studies largely agree that multimodal interactions using voice and gesture in tandem or sequence, as well as optionality for issuing certain commands in both modalities, appear more promising from both technical and user experience standpoints.

Researchers suggest "interacting with a pet" as an almost universally natural design metaphor for drone command. However, collectively, studies indicate that the composition of a universally natural or intuitive command repertoire is challenging, due to individual and cultural differences; although for some commands and populations, significant agreement is reported (e.g. the "stop" gesture among American participants [13]). This motivates future work on the design of intuitive documentation and "onboarding" procedures for gestural and vocal interactions with social drones, as well as end-user programming of custom gesture sets for drones (see [8, 9]).

Perceived Social Role

What kinds of existing conventions—e.g. privileges, responsibilities, expectations—around social roles assigned to living beings are relevant for drone behavior?

While a diverse array of task- and context-based functions and roles for drones have been explored (e.g. "assistant," "toy," etc. [35]), studies most commonly suggest that people are inclined to and comfortable with using a "pet" metaphor for interacting with drones. Qualitative findings support the "pet" metaphor from several angles. For example, human interpretations of drone behavior have been reported to be often based on expectations formed by animal behavior [13]; gesture- and voice-based interactions with drones have been observed to induce, over the course of studies, attachment and socialization as if with a pet [48]; and the capability to "train" a drone like a pet has been preferred over direct and absolute control [37]. The strength of how much this metaphor influences user sentiment and behavior may vary based on cultural factors [20], but findings converge over the existence of such influence. This evidence points to opportunities for future work around transferring knowledge from animal cognition and behavior, as well as human-animal interactions and animal training, to drone design.

Tactility Perception

To what degree do people perceive the drone design under investigation as something they can touch, hold, and manually manipulate?

Even though airborne tangible UIs appear to hold much future potential for novel interaction designs, studies agree that potential users rarely recognize propeller-driven drones as providing safe and stable touch affordances in early encounters. However, as quick as during the progression of a single user study, participants have been observed to adapt well to the concept—provided, understandably, that the moving parts are appropriately enclosed in protective exteriors [3, 78].

While we have not come across a dedicated study on the effect of drone size on the perception of tactile affordances, greater aversion to touching a drone has been observed in studies with larger drones. Specifically, studies using compact prototypes with a greatest dimension of 12 cm have yielded favorable results [39], in contrast to earlier studies with full-size drones [3, 78]. Finally, more favorable results with tactile affordances have been reported in the context of sports and exercise, where presumably participants felt prepared to respond reflexively to unexpected drone behavior [78].

5 DISCUSSION AND CONCLUSION

In principle, the aim of this paper is to provide a springboard for future design research and practice on social drones. Our effort to fulfill this aim efficaciously comes with certain limitations in terms of methodology and presentation. A principal limitation of the framework we used to characterize design knowledge derived from empirical studies is that it does not explicitly take context into account. In many cases, associations between HCCs and DDCs are highly context-dependent; for example, desiderata for a drone intended to fulfill a particular purpose indoors may be radically different from those for one intended to work outdoors. However, adding this additional layer would result in a level of complexity that would make both analysis and presentation intractable, despite the small size of our corpus. Furthermore, our analysis concentrates on findings and implications, at the expense of learnings derived from the *process* of implementing them, which may be significant in themselves (see [77]). Taking these limitations into account may serve future work intending to apply a similar framework to other domains.

Further, in terms of presentation, both the present format and the online repository in its present form are limited in that they do not afford interactive filtering. An interface where granules of design knowledge, systematically organized, can be filtered and visualized in various forms could be the subject of future work, and the repository we contribute can be used as a resource in its development.

As a side note, we wish to point out that in order to guide our own empirical studies with interactive drones, we have searched our corpus for the keywords "IRB, institution, board, ethics, approve, approval," and did not find any relevant results; while only 7 papers in the corpus explicitly stated that written statements of informed consent have been obtained from participants. We suggest that explicit reporting on how safety measures and liability protection are implemented in studies with co-located drones can serve the community.

In delimiting our focus to human-centered studies on autonomous flyers in inhabited environments, we recognize having left out a body of knowledge that the works in our corpus build on. Particularly, the broader discipline of human-robot interaction (HRI), as well as disciplines studying interactions between humans, are essential to informing almost all of the design research we reviewed. For example, much work on social drones starts out by questioning whether existing knowledge and techniques from HRI apply to flying agents [13, 23, 76]. Linking sources of knowledge from HRI literature to our corpus is a logical next step in adding value to the online repository we created.

In conclusion, motivated by recent trends in research and commerce around social drones, this paper contributes a consolidation of existing human-centered design knowledge on the subject. Based on current trends (see Figure 3 and [69]), we expect interest and knowledge in this domain to grow rapidly in the future. We hope that our contributions serve to fulfill this expectation.

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