IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 21, 2019, accepted November 4, 2019, date of publication November 18, 2019, date of current version December 2, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2953900

The State-of-the-Art of Human–Drone Interaction: A Survey

DANTE TEZZA, (Member, IEEE), AND MARVIN ANDUJAR, (Member, IEEE)
Computer Science and Engineering Department, University of South Florida, Tampa, FL 33559, USA
Corresponding author: Dante Tezza (dtezza@mail.usf.edu)

ABSTRACT Drones have expanded from military operations to performing a broad range of civilian applications. As drone usage increases, humans will interact with such systems more often, therefore, it is important to achieve a natural human-drone interaction. Although some knowledge can be derived from the field of human-robot interaction, drones can fly in a 3D space, which essentially changes how humans can interact with them, making human-drone interaction a field of its own. This paper is the first survey on the emerging field of human-drone interaction focusing on multi-rotor systems, providing an overview of existing literature and the current state of the art in the field. This work begins with an analysis and comparison of the drone models that are commonly used by end-users and researchers in the field of human-drone interaction. Following, the current state of the field is discussed, including the roles of humans in HDI, innovative control methods, remaining aspects of interaction, and novelty drone prototypes and applications. This paper concludes by presenting a discussion of current challenges and future work in the field of human-drone interaction.

INDEX TERMS Drone, human-computer interaction, human-drone interaction, human-in-the-loop, human-robot interaction, unmanned aerial vehicle.

I. INTRODUCTION

Drones, also known as unmanned aerial vehicles (UAV), are robots capable of flying autonomously or through different control modalities such as joysticks, smart-phones, the human brain, voice, gestures, and others. Until the early 2000s, drones were complex systems commonly seen in the military world and out-of-reach for civilians. Modern advancements in hardware and software technologies allow the development of smaller, easier to control, and lower cost systems. Drones are now found performing a broad range of civilian activities (e.g. photography during extreme sports activities, construction surveillance, racing, agriculture, among others) and their usage is expected to keep increasing in the near future. The United States Federal Aviation Administration (FAA) expects that by 2022 the number of registered drones in their database might be as high as 3.8 million units [1]. The FAA drone registration forecast can be seen in Table 1, the baseline number was calculated by FAA through observation of the number of registrations, expert opinions, review of industry forecast, and market/industry research. However, the report does not specify how the low and base scenarios are calculated and does not provide a low scenario for commercial drones.

TABLE 1. Drone registration forecast according to the FAA with a low base and high estimates for drone registration until 2022 [1].

FAA Drone Fleet Forecast (millions of units)							
	Hobbyist			Commercial		Total	
Year	Low	Base	High	Base	High	Base	High
2018	1.5	1.6	1.73	0.158	0.168	1.758	1.898
2019	1.76	2.0	2.35	0.229	0.268	2.229	2.618
2020	1.87	2.2	2.73	0.312	0.410	2.512	3.14
2021	1.92	2.3	2.94	0.407	0.604	2.707	3.544
2022	1.96	2.4	3.17	0.451	0.717	2.851	3.887

This paper focuses on the interaction among humans and multi-rotor drones, which are capable of flying in a 3D space, hovering, and vertical takeoff and landing. Such drones can range from small toy-grade remote-controlled aircraft to fully-autonomous systems capable of decision-making and carrying a large variety of sensors. Multi-rotor drones are widely used for photography, structural inspections, and sports; however, their application goes far beyond. As an example, monitoring of animals' distributions is a time-demanding task that is usually performed by foot or manual

The associate editor coordinating the review of this manuscript and approving it for publication was Maurizio Magarini.

analysis of videos; drones can greatly automatize this process assisting in nature conservation [2]. Another example of how these systems can be applied is to assist in natural disasters response, as they can be used to search for victims, delivery of supplements, or even as fire extinguishers [3]–[5].

Human-robot interaction can be defined as ''a field of study dedicated to understanding, designing, and evaluating robotic systems for use by or with humans'' [6], analogously, human-drone interaction (HDI) can be defined as the study field focused on understanding, designing, and evaluating drone systems for use by or with human users. Although some knowledge can be derived from the field of human-robot interaction, drone's unique characteristic to freely fly in a 3D space, and unprecedented shape makes human-drone interaction a research topic of its own. Human-drone interaction is a broad research field, for instance, a researcher can design new drones' shapes with friendly-like appearance, while another researcher can focus on designing new user interfaces that allow non-skilled pilots to accurately operate drones without extensive training.

As drone usage continues to increase, humans are likely to be seeing or using drones in their everyday lives, therefore it becomes important to study the interaction among humans and such systems. As HDI is a relatively new field, this work was motivated to summarize the existing literature and present the state-of-the-art in the field. This survey shows that the current state of the art research in human-drone interaction consists of evaluating and developing new control modalities, enhancing human-drone communication, evaluating interaction distance, and developing new use cases. These four major fields of HDI are displayed in Fig. 1 and discussed throughout this paper. Additionally, recent research in HRI has been focusing on social robots [7], similarly, HDI research is starting to focus on social drones. It is important to mention that this paper does not discuss fixed-wing drones, which are less applicable to HDI due to their limited maneuverability and lack of hovering ability. Researchers that are not familiar with the fundamentals of drone technologies can acquire the necessary background to understand the concepts presented in this paper in [8].

The remaining of this paper is organized as follow. Section II presents an analysis of which drone models are commonly used by hobbyists, professional pilots, and by researchers. This section also presents a comparison of

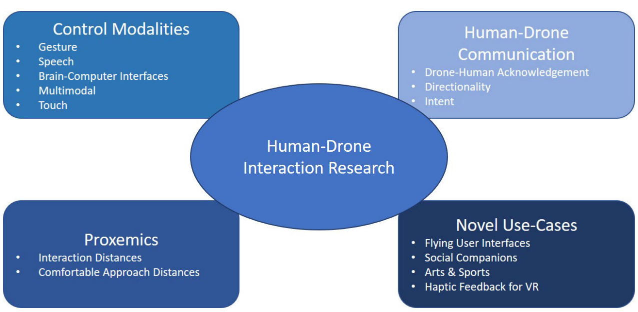

FIGURE 1. The four major fields of Human-Drone Interaction research.

features of the most common drone models, giving insights on their capabilities and limitations. Section III discusses the roles of humans in HDI, and the evolution of research in the field by presenting the number of publications in the field chronologically. Section IV presents innovative drone control methods, including gesture, speech, brain-computer interfaces, and others. Section V discusses remaining aspects of human-drone interaction, such as comfortable distances, communication, and emotion encoding. Following, Section VI presents research studies with innovative drone prototypes and use-cases in the HDI field. In section VII, it is presented the current challenges and future directions in HDI. Concluding, Section VIII summarizes this survey paper.

II. DRONE MODELS

This section presents an analysis of the most commonly used multi-rotor drones by end users and researchers, as well as a comparison of these model's specifications.

A. POPULAR DRONE MODELS

Today's market presents a wide variety of commercial-off-the-shelf drone models. The United States Federal Aviation Administration (FAA) requires any drone weighing at least 0.55 pounds to be registered on their database. Analyzing the FAA database allows us to estimate the number of drones being used and which are the most popular manufacturers and models. Until November 2017, a total of 836,796 aircraft were registered for hobbyists and 106,739 for commercial purposes [9].

The application areas where commercial drones are being mostly used can be seen in Table 2. Fig. 2 describes the number of registrations per manufacturer until November of 2017 (last public release of the database). The graph shows that most registered drones are manufactured by DJI and according to [10] they control 72% of the commercial drone global market. The easiness of use and a large variety of models for different applications (hobbyists, professional cinematography, and industrial applications) are possible explanations for why DJI dominates the commercial market.

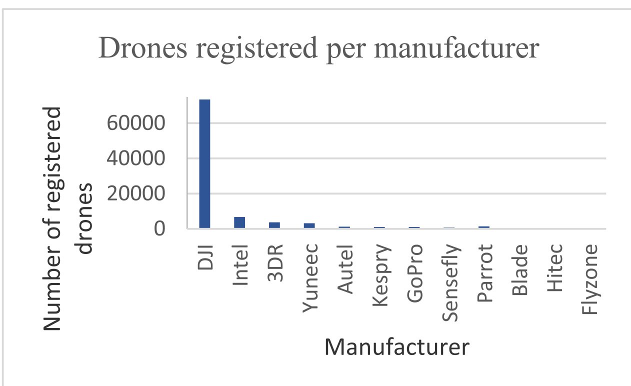

FIGURE 2. Number of drones per manufacturer registered in the FAA until November 2017. Only 30 mostly registered drone models are taken into consideration [9], [11].

TABLE 2. Common uses of commercial drones according to the FAA [1].

Application	Percentage
Real State & Aerial Photography	48%
Industrial Inspection	28%
Agriculture	17%
Insurance	4%
State & Local Government	3%

B. DRONE MODELS USED ON PREVIOUS RESEARCH

From the papers reviewed in this survey, 56 of them described a project where a drone or a prototype was used; the remainder of the papers discussed other aspects of HDI (e.g. statistics and use case scenarios). The models of the drones used in these papers can be seen in Fig. 3. As shown in the figure, most studies (57%) used the Parrot ARDrone as a base for their prototype or to conduct an experiment. This shows a considerable difference from the drones used by end-users where DJI dominates the market (see Fig. 2). Parrot drones provide an easy-to-use software API allowing for quick prototyping, which is likely the reason they are the researcher's first choice. A comprehensive overview of the ARDrone including its hardware, software, and instructions on how to use it as a research platform can be found in [12]. Although the Parrot ARDrone is widely used for research, this model was discontinued by the manufacturer.

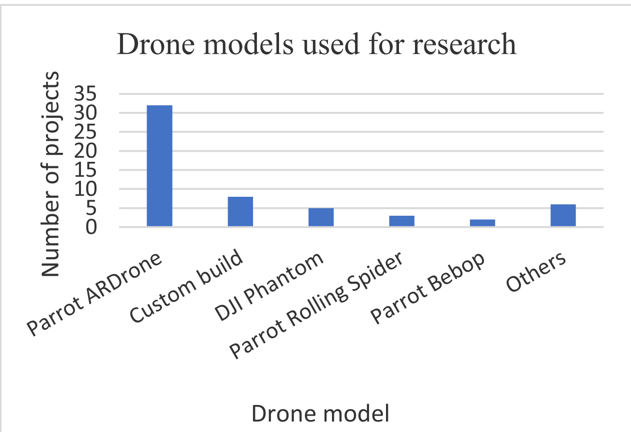

FIGURE 3. Analysis of drone models used during the research studies reviewed in this paper.

C. DRONE MODELS COMPARISON

The specifications of the currently available commercial-off-the-shelf drone models can be seen in Table 3. As shown in the table, current drones can reach 31 minutes of flight time, speeds up to 93 kilometers per hour, 8 kilometers of range and their price range from $99 to $2999.

III. HUMAN-DRONE INTERACTION RESEARCH

A. ROLES OF HUMANS IN HDI

Humans play different roles when interacting with drone systems. Their role is dependent on the drone's application and its level of autonomy. The human can act as an *active controller*, in which the pilot directly controls the drone with a control interface to perform a task. For example, to take pictures of a landscape or participate in a drone racing competition. Another role is of a *recipient*, in this case, the user does not control the drone, but it benefits from interacting with it. As an example, a user walking in the street might be approached by a drone holding an advertisement screen [13], or even a user receiving a package delivered by a drone [14], [15]. Humans can also interact as *social companions* with drones, in this case, the user might or might not be able to control the drone movement, but it holds a social interaction with it. An example of such interaction is Joggobot, in which the drone flies along with humans that are jogging providing a social interaction [16]. Lastly, autonomous drones require users to act as *supervisors.* Although modern drone systems can fly fully autonomous, a human is still required either to pre-program the drone behavior (e.g. plan flight mission) or to supervise the flight itself (e.g. monitor an autonomous inspection flight in real-time) in case of emergency. Additionally, it is worth mentioning that even applications in which the drone is acting autonomously, a human can still be in the loop in the form of a recipient, for example, to receive the package of a drone delivery service, or to read the information of an advertisement drone. These roles of humans in HDI are summarized in Table 4.

B. HDI RESEARCH OVER TIME

The field of HDI is relatively new in the research community. A search in Google Scholar filtering the results by publication year can demonstrate how this field has evolved over time. The number of search results for ''human-drone interaction'' by year is shown in Fig. 4. Until the year 2014, there were only two results for this search, but the number changes to 180 when publications up to 2018 are included. Different search queries containing a combination of the words ''drones, UAV, and human-in-the-loop'' were also searched, but the results were mostly related to drone technologies for warfare and ethics related to drone usage. Therefore, for purposes of demonstrating how the HDI field evolved over time, Fig. 4 only contains results for the query ''human-drone interaction''.

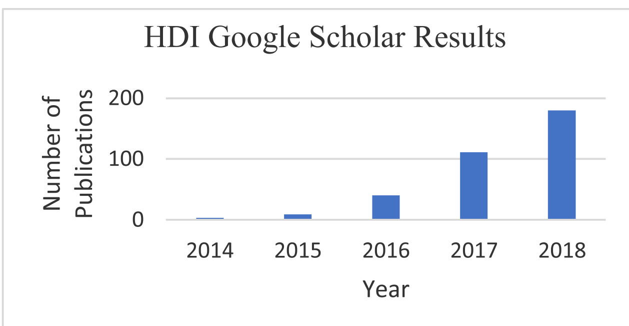

FIGURE 4. Number of publications found on Google Scholar using ''human-drone interaction'' as a query.

TABLE 3. Comparison of commercial-of-the-shelf drone models.

Brand	Model	Flight Time (min)	Speed (km/h)	Weight (grams)	Range (km)	SDK	Picture Resolution	Video Resolution	Control Interface	Obstacle Avoidance	Price
DJI	Phantom 3 SE	25	58	1280	4	Mobile	12MP	4k 30fps	RC, Phone	No	$599
DJI	Phantom 4	30	72	1388	7	Mobile	20MP	4k 60fps	RC Phone	Yes	$1199
DJI	Mavic Pro	27	64	734	7	Mobile	12MP	4k 30fps	RC Phone	Yes	$999
DJI	Mavic Air	21	67	430	4	Mobile	12MP	4k 30fps	RC Phone	Yes	$799
DJI	Mavic 2 Pro	31	70	907	8	Mobile	20MP	4k 30fps	RC Phone	Yes	$1499
DJI	Spark	16	50	300	2	Mobile	12MP	1080p 30fps	RC Phone	Yes	$399
DJI	Inspire2	27	93	3440	7	Mobile	Sold separately	Sold separately	RC Phone	Yes	$2999
Parrot	Bebop2	25	59	500	0.3	Yes	14MP	1080 - 30fps	RC and Phone App	No	$399
Parrot	Anafi	25	53	320	4	No	21MP	4k-30fps	RC Phone	No	$699
Ryze	Tello	13	27	80	0.1	Yes	5MP	720p - 30fps	Phone App	No	$99
Wingsland	S6	10	27	230	0.1	No	13MP	4k - 30fps	Phone App	No	$199
Intel	Aero RTF	20	53	865 wo/ battery	0.3	Yes	8MP and Realsense camera	1080 – 30fps	RC	Yes	$1099
Yuneec	Breeze	12	18	385	0.1	No	13MP	4k - 30fps	Phone App	No	$199
Yuneec	Typhoon 4k	25	29	1700	0.8	No	12MP	4k-30fps	RC	No	$599
Yuneec	Typhoon H Pro	25	69	1950	1.6	No	12MP	4k - 30fps	RC	Yes	$1199
Autel	X-Star Premium	25	56	1420	2	No	12MP	4k - 30fps	RC	No	$749
Autel	Evo	30	70	863	7	No	12MP	4k - 60fps	RC Phone	Yes	$999

TABLE 4. Roles of humans in HDI.

Role	Example
Active controller	Pilot controlling a drone during a photoshoot or racing competition.
Recipient	User watching advertisement displayed by a drone[13] or receiving a package delivery[14,15].
Social Companion	User performing physical activities (e.g. jogging) in companion of a drone [16].
Supervisor	Pilot supervising a wildlife monitoring autonomous mission [2].

IV. INNOVATIVE CONTROL INTERFACES

Originally, drones were used for military applications and required highly trained pilots for operation due to its complex user interfaces. As drone technologies became more ubiquitous and affordable, researchers started to shift interface design towards modern user interfaces that no longer limits drone control solely using a remote controller or a ground control station. These innovative methods, which are also known as natural user interfaces (NUI) allow users to interact with drones through gesture, speech, gaze, touch, and even using brain-computer interfaces (BCIs) such as electroencephalography (EEG). Each control interface impacts how the pilot interacts with the drone in various aspects, such as training period, accuracy, latency, interaction distance; in this section, we present innovative control modalities and how they affect the pilot's experience. A summary of the advantages and disadvantages of each NUI, as well as the traditional remote-controller interface, can be seen in Table 5. Each NUI is further discussed in the sub-section below.

The main goal of natural user interfaces is to achieve an intuitive control method, which is defined as an interface that works at user's expectations [17]. Natural user interfaces allow non-expert users to control drones with a shorter training period, reduced workload and possibly even decrease aircraft crashes. A previous study proposed a series of design guidelines for natural user interfaces: (1) input vocabulary must employ mental models that are known to the targeted user, (2) natural behavior of users must be analyzed to discover user-defined mental models, (3) mixing gestures from different mental models in an input vocabulary should be avoided, (4) and important aspects (such as physiological, cultural differences, application, and ergonomics) must be considered in the final input vocabulary [17]. Additionally, the concept of using mental models when designing a user interface can enhance the final product. Mental models for

TABLE 5. Control interface summary.

Control Interface	Advantages	Disadvantages
Remote Controller	Low-latency Precise control	Less intuitive than natural user interfaces.
Gesture	Natural/intuitive Most drones already carry a camera Short training period	Collocated interaction only High latency and lower control precision when compared to others
Speech	Natural/intuitive Short training period Handless	Propeller sound can impact speech recognition Not all drones already have microphones Collocated interaction only
BCI	Handless Accessible to users with physical disabilities Ability to measure pilot's affective and cognitive state	Longer training periods Lower control accuracy when compared to others Slower input and output response
Touch	Natural/intuitive Short training period	Collocated interaction only Requires safety measures (e.g. propeller guards)
Multimodal	Can combine benefits from various modalities	Possible higher complexity and cost

HDI are classified as imitative, instrumented and intelligent [17]. An imitative control happens when the drone simple copies an action performed by the user, for example, the aircraft can fly translating the pilot's hand movement directly to aircraft attitude. Instrumented interaction requires an intermediate link, which can be a physical object or an imaginary one; such as the use of a physical or imaginary joystick. An intelligent type of interaction allows the operator to treat the system as an intelligent system and send high-level commands such as a ''follow me'' command.

An elicitation study evaluated natural human-drone interaction techniques using a Wizard of Oz (WoZ) approach [18]. In this user study, 19 participants were asked to complete a set of tasks of different complexities using any interaction technique they considered natural. A DJI Phantom 2 with propeller guards was used in this study and participants were informed that its behavior was being simulated. To avoid verbal biasing, each task was written on a card that participants were asked to pick out of a stack. During the first phase, participants had to perform 18 tasks without receiving any instructions, at the end of each interaction they were asked to recall and explain their actions using a post-task and think aloud technique and rate the session in terms of suitability and simplicity. During a second study phase, participants were given interaction suggestions and asked to perform 4 tasks; this phase allowed an evaluation to see if participants changed their interaction strategy. Each session was recorded, it lasted between 1 to 1.5 hours, and participants were rewarded $15 for their time. At the end of the experiment, a total of 216 unique interactions were observed. From these interactions, it was observed that 86% were gesture-based, 38% were sound-based, and 26% used both gesture and sound (multi-modal). This study also observed that 90% of the participants felt in control of the drone, and 95% felt that the human-drone interaction was natural. Safety is a concern of studies performed with flying robots, nonetheless, in this study 16 out of 19 participants reported feeling safe when interacting with the drone.

The above study was replicated at a Chinese university to evaluate how cultural differences impact HDI [19]. The same methodology and drone model were used during the study replica, which was performed with 16 participants. Similarly, 86% of Chinese participants performed gesture-based interaction, however a higher number used speech (58%) and multi-modal interaction (45%). A comparison between the results achieved in the USA and China shows that Chinese participants are more prompt to multimodal interaction than American users, confirming the hypothesis that cultural differences impacts HDI.

A modified version of this study was performed to evaluate if participants will instinctively use touch as a means of interacting with the drone [20]. This was a between-subjects study with 24 participants divided into two groups, one of them interacting with a standard Parrot ARDrone, while the other group interacted with a modified safe-to-touch version of the same model (protective cage). The methodology of the study differed from the original [18] as participants were not informed that the drone was being controlled through a WoZ, instead of cards participants were given visual images of the drone state before and after the task, and only 12 tasks were performed. Among the 12 participants that interacted with the safe-to-touch 58% of them used touch, and 39% of all interaction was touch-based, suggesting that it is a natural interaction technique. Feedback provided by participants states that interacting with the safe-to-touch drone was significantly less mentally demanding than the unmodified drone.

A. GESTURE

Studies demonstrate that when users are asked to interact with a drone without any instruction, gesture interaction is the primary choice of most users [18]–[20]. Collocated interaction with drones is more natural using gestures rather than a joystick, which positively affects the social aspects of HDI [21]. Previous studies suggest four design rules for gesture-based systems: (1) gestures should be natural and easy to perform, (2) information in the captured images should be related to gestures, (3) a clear distinction between the background and the gesturing body is necessary, (4) and data processing shall be done with minimal delay [22].

A straight-forward approach to implement a gesture-based system is to use a Kinect device to extract spatial information and recognize postures. This approach was successfully used for both collocated [23], [24] and teleoperation control [22]. To create an immersive flight experience, a Kinect device can be combined with an Oculus Rift virtual headset to control drones [25]. A setback from using a Kinect device for human-drone interaction is that the system end-to-end latency is relatively high, measured at around 300 milliseconds [22], [23]. Hand-gestures were also successfully used to control drones, either through a Leap motion controller [26], [27] or electromyography (EMG) signals captured with a BioSleeve [28].

TABLE 6. Summary of gesture controlled multi-rotor drones.

Publication		Prototype Specifications			User Study	
Authors	Year	Brand	Model	Additional Equipment	Design	Participants
Ng et al. [21]	2012	Parrot	ARDrone		Wizard of Oz preliminary evaluation	Non-specified
Sanna et al. [23]	2013	Parrot	ARDrone	Joystick(not specified) Microsoft Kinect Iphone	Comparative study	4
Monajiemi et al. [32]	2013	Parrot	ARDrone		No user study.	
Ikeuchi et al.[25]	2014	Parrot	ARDrone	Microsoft Kinect Oculus Rift	No user study	
Stoica et al. [28]	2014	DJI	Phantom 2	BioSleeve	Preliminary study	Non-specified
Nagi et al [31]	2014	Parrot	ARDrone		No user study	
Cauchard et al. [18]	2015	DJI	Phantom 2		Wizard of OZ elicitation study	19
Mashood et al. [22]	2015	Parrot	ARDrone	Microsoft Kinect	No user study	
Sarkar et al. [26]	2016	Parrot	ARDrone	Leap Motion Controller	No user study	
Fernandez et al. [27]	2016	Parrot	ARDrone	Leap Motion Controller	Evaluation study	Non-specified
Landay et al. [19]	2017	DJI	Phantom 2		Wizard of Oz elicitation study	16
Abtahi et al. [20]	2017	Parrot	ARDrone	Protective propeller cage	Between-subject WOZ elicitation study	24
Sun et al. [30]	2017	DJI	Matrice 100	Intel NUC onboard computer Logitech webcam	Evaluation study	7

Gesture recognition can also be achieved using cameras and computer vision. Many drones already have an onboard camera, which can be used for gesture recognition without requiring extra sensors that increases payload [29], [30]. Face pose detection can be used to estimate the drone's relative position to the user [31], the user can move the drone by simply pointing at the desired direction. A prototype was built using the Parrot ARDrone and its onboard camera. The drone first detects a human face, initializing the interaction. A Viola-Jones face detector algorithm is used, and a Kalman filter is also used to track the human face and reduce false positives. A face score system was developed, which detects the direction of the user's face and allows the drone to estimate its position and distance with respect to the user. The pilot can send the drone to a specific direction by pointing his hand, colored gloves were used to allow easier detection of the gestures.

The integration of face recognition and gesture was also studied by [32], where users can select which drones to add or remove from a group of drones through face engagement and gesture control the selected quad-copters through. This approach allows the creation of teams by individually adding or removing drones from the group through face-engagement and hand gestures. Face engagement is defined as the process of using eye and gaze contact to establish an interaction with the system. Prototypes were built using Parrot ARDrones that communicated to each other and the GCS through Wi-Fi connection. Each drone uses OpenCV to detect and track the user's face. A distributed election among the drones detects which quadcopter the user is wishing to engage. The drone with the most accurate face detection is considered active and proceeds to detect user's hand gestures. A user can add a drone to a team by looking at the desired drone and raising his right hand, similarly, a drone can be removed from a group by raising a left hand. The user can start a mission by waving both hands, and the command will be sent to all drones in the group. For this experiment, the mission was to simply perform a flip action, but it can be elaborated to more complex autonomous missions at a later work. For distinction purposes, the drones currently on the team fly at an altitude 0.2 meters higher than others. During the first experiment, a marker-based localization algorithm was used to position the three used drones, individual engagement and team control was considered successful in 10 out of 15 trials. A second experiment was performed with only two drones and a feature-based localization algorithm instead for positioning, in this case, 8 out of 10 trials for engagement and team control were successful.

A summary of papers and user studies related to gesture control can be seen in Table 6, which also describes the prototype and additional hardware specification. This survey on gesture control suggests that it is an intuitive control modality, with the advantages of easy control, and shorter training periods. Additionally, it presents the benefit of not requiring the user to hold external devices such as a joystick and can even be used with the onboard sensors solely. However, this method might not be the best approach to applications that require fine and precise control, as it does suffer from a higher latency and lower accuracy than other methods such as a remote controller.

B. SPEECH

Studies designed to elicit natural user interfaces showed that 38% of American users [18] and 58% of Chinese users [19] used speech as a method of interaction; which suggests that it is an intuitive control method (see Section IV). However, speech control has not yet been thoroughly explored by HDI researchers. Speech control can be considered easier than other methods (e.g. remote controller), as all that it is required is for the pilot to memorize voice commands, leading to shorter training periods. However, similarly to gesture control, the speech recognition can add latency to the system, limiting its applications. Additionally, controlling drones through speech presents some unique challenges, the fast-spinning propellers creates a loud noise that can

TABLE 7. Summary of brain controlled multi-rotor drones.

Publication		Prototype Specifications				User Study
Authors	Year	Brand	Model	BCI Equipment	Number of Channels	Participants
LaFleur et al. [35]	2013	Parrot	ARDrone	EEG – Neuroscan SynAmps	64	5
Kosmyna et al. [40]	2014	Parrot	ARDrone	EEG – g.Tec USBAmp/g.Sahara	16	25
Kosmyna et al. [41]	2014	Parrot	ARDrone	EEG – g.Tec USBAmp/g.Sahara	16	25
Kosmyna et al. [42]	2015	Parrot	ARDrone	EEG – g.Tec USBAmp/g.Sahara	16	24
Kim et al. [43]	2014	Parrot	ARDrone	EEG - Emotiv Epoc	14	5
Shi et al. [44]	2015	Custom built		EEG – Neuroscan NuAmps	40	6
Coenen [45]	2015	Parrot	ARDrone	EEG – BioSemi	64	1
Khan et al. [46]	2015	Parrot	ARDrone	NIRS – Nirx / EEG – g.tec g.MOBIlab	6 (NIRS) + 8 (EEG)	3
Lin et al. [47]	2015	Parrot	ARDrone	EEG – Emotiv Epoc	14	8
Zhang et al. [48]	2015	Parrot	ARDrone	EEG – Emotiv Epoc	14	-
Tezza et al. [49]	2019	Virtual drone		EEG – Emotiv Insight	5	30

decrease the accuracy of voice recognition. Another issue is that users are limited to collocated interaction if the voice-recognition is being performed onboard, as the drone needs to be close to the user to acquire the voice commands. This issue does not affect systems where a ground-control station is used to decode voice commands and control the drone.

A prototype built using the Parrot ARDrone and Aerostack framework can be controlled through voice commands [27]. In this project, the pilot uses speech to interact with a ground control station, which sends control commands to the drone. Voice processing is done using the ROS package implementation of the Pocket Sphinx library, a speech recognition system developed at Carnegie Mellon University. The current version has a control dictionary of 15 commands but can be further expanded to include new functionalities. The software package listens for a simple one to three-word tasks, feedback is provided through a voice synthesizer when a detection is made, and a command sent to the drone. Users that tried the system provided positive feedback, and most of them expressed that talking to a drone was like interacting with a pet. Speech has also been used as an input channel for multimodal ground control stations [33], and direct multimodal interaction [29], [34]. As these projects include more than one interaction technique, they are further explained in the multimodal section below.

C. BRAIN-COMPUTER-INTERFACE/BRAIN-CONTROLLED DRONES

Brain-computer interface devices have broad potential as assistive technologies and novelty control methods. Since 2010 researchers have been exploring the use of BCI's to control unmanned aircraft (fixed-wing), and in 2013 the first brain-controlled multi-rotor project was published [35]. Additionally, the first brain-controlled drone race was held in 2016 at the University of Florida [36], followed by a race at the University of South Florida [37] and the University of Alabama [38]. To control drones with brain-signals the pilot must wear some form of BCI headset, the most common being Electroencephalography (EEG) headsets. These devices measure the brain's electrical activity on human's scalp, which are decoded using machine learning algorithms to control physical systems using brain-waves.

A summary of brain-controlled drones' literature can be seen in Table 7, including the drone models, and BCI device specifications. The table shows that most projects use EEG based BCIs. Additionally, there are hybrid BCI approaches, which combine EEGs with other physiological sensors and other forms of control that is not brain-based. A comprehensive survey on brain-computer interfaces for unmanned aerial vehicle control can be found in [39]. Although successful control was achieved for up to three degrees of freedom, the authors conclude that interaction with BCIs is still more limited than other control interfaces and further research is required to increase fidelity and robustness of these systems before they migrate from laboratories to user's homes [39]. Once BCI reliability and accuracy achieve similar levels to other control modalities, this type of control will allow hands-free interaction and accessibility for disabled users. Additionally, BCI's can be used to measure the pilot's mental state and adapt the drone behavior and interface accordingly, for example, the system could adapt its user interface if it detects that the pilot workload levels are too high.

D. MULTIMODAL

Integrating different interaction methods can combine the advantages of each. Furthermore, previous work demonstrates that 45% of Chinese users [18] and 26% of American users [19] naturally use multi-modal interaction with drones. A summary of the papers related to multimodal control can be seen in Table 8, along with the prototype specifications, in which control modalities are involved and performed user studies. A multi-modal approach can be used to create a direct interaction with drones, for example by taking off and landing through speech and controlling movement by gesture [29], [34]. In these studies, a quadcopter prototype can be controlled solely by using onboard sensors to detect gesture and speech interactions, without the need for any external devices. Users can command take-off and land through audio commands, which was implemented using Julius, an open-source voice recognition library. Take-off is accomplished by voice command, but the propeller sound during flight creates too much noise for voice recognition, therefore the landing command is a whistling sound which has a distinct frequency from the propellers sound. Movement during flight

TABLE 8. Summary of multimodal controlled multi-rotor drones.

Publication		Prototype Specifications			User Study	
Authors	Year	Brand	Model	Type of Control	Design	Participants
Jones et al. [50]	2010	Virtual Drone		Speech + Gesture	Exploratory study (2 experiments)	10 (1st experiment) 9 (2nd experiment)
Miyoshi et al. [29]	2014	Custom built		Speech + Gesture	No user study	
Miyoshi et al. [34]	2014	Custom built		Speech + Gesture	Evaluation study	4
Cauchard et al. [18]	2015	DJI	Phantom 2	Speech + Gesture	Wizard-of-Oz elicitation study	19
Fernandez et al. [27]	2016	Parrot	ARDrone	Leap Motion Controller	Evaluation study	Non-specified
Landay et al. [19]	2017	DJI	Phantom 2	Speech + Gesture	Wizard-of-Oz elicitation study	16
Abtahi et al. [20]	2017	Parrot	ARDrone	Speech + Gesture + Touch	Between subject Wizard-of_oz elicitation study	24

is controlled by following hand movements wearing colored gloves. During the flight, if a hand is not recognized, the quadcopter simply hovers on the location. A pilot evaluation was performed with four participants, two of them being familiar with the project while the other two were not, and all participants were able to successfully control the system.

Virtual reality environments have been used for an exploratory study to investigate multi-modal interaction to control a swarm of drones [50]. This project presented a virtual environment of grass fields with landmarks (trees, wood and rock piles), where the users must control a swarm of 10 drones to search and rescue an individual. Users can control the drones using gestures and speech, but a Wizard of Oz technique was used to simulate the drone response. A first exploratory study was performed with 10 participants, each having 1 practice and 4 experimental trials. Participants were asked to control the team of drones over the landmarks until the target was found, time was emphasized as the experiment was simulating a search and rescue scenario. Observed interaction was classified as pointing and herding gesture actions, and high and low-level voice commands. User feedback stated that depth perception was an issue, as they could not precisely estimate the location and speed of the drones. A second experiment was performed using the same procedures as the previous, but participants were given a set of gesture and speech commands they could use to control the swarm. The command set was built based on the feedback received from the first experiment. To address the depth perception issue, half of the participants used a modified version of the system where fake shadows were projected in the ground below the drone. Results of the experiments state four design implications: (1) commands should be clear and well defined, but allowing some level of flexibility; high-level commands such as ''go to that tree'' require less interaction effort and should be given priority; (2) feedback is very important, users need to be informed that the system received and understood the command; (3) depth perception is an issue on this type of virtual reality environment, but adding shadows to the drones significantly addressed the issue; and (4) participants wanted more data in the interface.

There are three flows of information between users and ground control stations, which can be summarized as follow [33]. The first flow is from the operator to the ground control station (GCS), as the user controls the system. The second flow goes from the GCS to the user, providing system data, state, and feedback. Lastly, the operator state can also be used to provide information to the GCS, for example by adapting ground control stations using heartbeat or EEG signals as passive input channels. Multi-modal interaction can enhance all three data-flows by increasing the number of communication channels, addressing high information loads, and allowing communication within a variety of environmental constraints [33].

E. OTHER CONTROL INTERFACES

Manufacturers recently started to design safe-to-touch drones, features such as hand landing are already available to commercial drones like the DJI Spark, Ryze Tello, and others. A study designed to elicit natural user interfaces found that 58% of participants used touch interaction when the drone was enclosed in a safe-to-touch frame (see Section IV), and that interacting with a safe-to-touch drone is mentally less demanding than a traditional design [20]. Another control modality is to use Gaze tracking to generate commands. Gaze allows two directional control, which can be combined with different input channels to fly drones in a 3D space. A comparison of different combinations of gaze and keyboard control found that the best approach is to use gaze to control pitch and yaw while controlling roll and altitude through the keyboard [35].

Birdly is a simulator that creates a virtual reality environment to allows users to fly like a bird. A modified version of Birdly described in [51] allows users to control an actual drone through body movements and the camera gimbal through head movement, creating an immersive flight experience. The author's goal was to develop an effective and natural embodied human-drone interaction that is easier to train and more immersive than traditional interfaces such as joysticks, keyboards, and touch-screens. To control the drone the user lays down on the simulator with arms wide open as it was about to fly like a bird. Roll and pitch movement is controlled by hand movements and the camera gimbal is controlled by head movement. The video stream from the drone is displayed on the user goggles, the simulator platform tilting provides vestibular feedback according to the drone attitude, and a fan pointed at the user adapts its speed accordingly to the drone speed. The authors decided to use a multi-rotor drone modified to act as a fixed-wing drone as it flies more similarly like a bird and provides an easier mapping to Birdly commands. A first experiment was performed with 42 participants using a virtual reality environment built with Unity 3D. During the experiment, 2 users felt nauseous and didn't complete the tasks. Out of the 40 participants, 20 tried the system utilizing a traditional joystick control and 20 tried using Birdly. Out of each group, 10 participants controlled the drone utilizing angle mode, and 10 controlled using acro mode. The best results were achieved using Birdly with angle control mode. Positive feedback was provided as Birdly allowed an immersive, enjoyable, and natural experience. A system prototype was built allowing the control of a drone utilizing Birdly and angle control mode, following the results achieved during the first experiment. To validate the system, a user with no prior experience was asked to fly the system for 5 minutes. He was able to accurately control the drone through the pre-determined flight path. The participant also provided a feedback score of 7 out of 7 for an enjoyable experience, 6 out 7 that he was in control of the flight trajectory and 5 out of 7 as the sensation of flight.

Flying head is another project that provides an innovative drone control method [52]. The drone movement is synchronized with the user head movement in terms of horizontal, vertical position, and yaw rotation. As the user head moves or rotates the head, the drone imitates the movement. Altitude can also be commanded through a Wii remote controller, allowing altitudes higher the user height. The drone's camera image is streamed to a head-mounted display (HMD), allowing the user to see the first-person view. The prototype consists of a Parrot ARDrone, an HMC Sony HMZ-T1 display, and an OptiTrack S250e motion capture system. Two user studies with 6 participants were performed to compare Flying head against a joystick control. During the first study, each participant had 3 sessions to control the drone to acquire 4 static markers placed around the room using both Flying Head and the joystick. The time required to complete the task using Flying Head was on average 40.8 seconds, while interaction with the joystick took 80.1 seconds. These results show the efficiency of Flying head as a control modality, a paired t-test from the average of each participant time resulted in a p-value of 0.007. During a second experiment, participants had to follow a moving target (toy train) around an oval lap using both Flying head and joystick control methods. Again, each participant performed 3 sessions and the percentage of time each was able to accurately follow the target was calculated. Flying head allowed participants to follow the train on average 59.3% of the time, while joystick control had a result of 35.8%; a paired t-test resulted in a p-value of 0.012. Another user study was performed with Flying Head to evaluate the system against a method where operators control the drone by moving a scaled-down dummy aircraft with his/her hand [53]. In this experiment the movement acquired by flying head was translated to drone movement in a 1:2 scale, and the dummy drone movement was scaled 1:2.5. Again, flying head provided better results as the average completion time for the required task with Flying head was 53.1s and 99.1seconds with the hand-synchronization method, which led to a p-value smaller than .01 in a paired t-test. Head-synchronization methods can be explored and used to create new aerial sports that allow users to overcome the human-physical limitation. [54].

An innovative control method is to utilize a scaled-down 3D printed map of the flying terrain and allow the pilot to draw the desired drone's flight path on the physical map model [55]. The drawn flight path and video stream from the drone is superimposed on the map using either an augmented reality handheld or head-mounted display (HMD). A proof of concept prototype was built using the Parrot Bebop drone, an iPad air as the handheld device and an Epson Moverio HMD. The user can interact with the 3D map using a pen to plan the flight and watch it once the drone starts to fly autonomously. In this project, the user interface is fully developed but the drone interface has not yet been developed, therefore as a proof of concept a Wizard of Oz approach was used to simulate the drone behavior.

V. DISTANCE, COMMUNICATION AND EMOTION ENCODING

As drone usage continues to increase, it becomes important to understand the different aspects of human-drone interaction. This section covers areas related to comfortable distances, human-drone communication, and emotion encoding in drones.

A. INTERACTION DISTANCE

The interaction distance between a drone and a human must be considered for smooth social interaction [56]. In the elicitation studies described in Section IV, the authors also analyzed the distance participants kept from the drones during the experiments. In [18], 37% of American users stayed within the intimate space from the drone (45cm), 47% stayed in the personal space (1.2 m) and the remaining 16% interacted within the social space (3.7 m). In [19], the authors demonstrate that Chinese participants interacted at a closer distance: 50% at the intimate space, 38% at the personal space, 6% at the social in the public space ($>$ 3.7 m). Such results demonstrate that the majority of users are comfortable getting to a close interaction distance with drones and that cultural factors influence proxemics in HDI, as Chinese participants got to closer proximity than American participants in studies [18], [19]. Another user study where drones approached users at different heights (1.80m and 2.13m) concluded that height played no significant impact in comfortable approach distance [57].

A human-centered design approach was used to prototype a social drone in [56]. At the first stage, 20 participants of a design study were asked to draw what they believed a social drone would look like starting from a DJI Phantom 3 silhouette and to answer a survey about the features such a drone would have. Results showed a strong agreement in a few aspects: an oval or round shape around the drone, facial features, colorful, and the use of a screen and audio for human-drone interaction. A second phase consisted of a focus group with 5 participants, who were given 20minutes to draw a social drone using the attributes and characteristics elicited during the first phase. Results from both the design study and focus group were taken into consideration to implement a social drone prototype, which was used for a proxemics study. Results demonstrated that users allowed the social prototype to get 30% closer (average 41inches) than a non-social prototype (average 54 inches). The same study observed that pet-owners and male users are more likely to have a closer interaction than non-pet owners and female users.

B. DRONE FEEDBACK

Studies have previously explored methods for acknowledgment of mutual attention between a drone and its user. A proposed system allows users to call the drone attention by waving its hands, the drone acknowledges that the user has its attention by wobbling sideways in the air and further interaction can start. This topic is also discussed in [58], where a comparison of four different drone acknowledgment gestures shows that users prefer a rotation in the yaw axis to indicate acknowledgment. The authors provide a series of design guidelines for drone acknowledgment gestures such as the preferred distance (1.80m), a clear distinction between gestures and other flight maneuvers, and gesture speed (yaw: 100deg/sec pitch: 66deg/sec roll:133deg/sec).

Natural human-drone communication is also necessary to achieve good interaction, especially in a collocated space. Previous research explored a drone's ability to communicate its intent to users [59]. In this study, the authors defined drone motion as a composition of trajectory, velocity, and orientation. To express intent through motion the authors manipulated movement primitives using arc trajectories, easing in and out of velocity profiles, anticipatory motions, and different combinations of the previous. A user study with a Unity simulation was performed to elicit the most efficient motion manipulations to demonstrate intent. Using the highest accuracy results achieved during the first study, a flying prototype was built with manipulations for the following tasks: approach person (easy in-out), avoid person (arc + ease-in-out), depart person (easy in-out), approach object (anticipate), and depart object (arc + ease-in-out). A second user-study was performed to test the prototype with 24 participants. Results demonstrated that all three hypotheses were correct: (1) collocated individuals will prefer working with a drone using manipulated flight paths, rather than baseline paths, (2) collocated individuals will view manipulated drone flight paths to be more natural and intuitive than baseline motions, and (3) collocated individuals will feel safer interacting with a drone using manipulated flight paths than baseline paths. This study successfully demonstrated the ability to enhance human-drone interaction by manipulating flight-path to communicate intent.

While a drone's ability to fly in a 3D space present unique advantages, they also pose a challenge in achieving effective human-robot interaction [60]. Current drones lack the ability to communicate effectively with its user, which makes it hard to interpret the system and can even lead to accidents. Another study related to human-drone communication explored efficient approaches to communicate the directionality of flying robots through visual feedback [60]. The authors developed a prototype ring consisted of 64 LED lights that are used to communicate directionality and can be attached to drones. Four high-level signal models were designed to inform directionality: blinker, beacon, thruster, and gaze. The blinker approach consists of blinking one-quarter of the ring at a 1Hz frequency to communicate intent to move in a specific direction, like an automobile blinker. The beacon can be compared to a light beacon that points the direction the drone is moving towards; a wider portion of the ring was lighten using a gradient brightness decreasing from the pointing direction to the sides. The thruster is an analogy to the light and flame produced in jet engines, therefore a small region of the ring in the opposite side of the direction was powered at high-intensity. Gaze was inspired by human eyes, two small areas on the ring (eyes) looking in the direction that the drone will fly. A user study with 16 participants was performed to evaluate the different lighting patterns. Users provided feedback after observing the drone perform different tasks utilizing each pattern. Participants were able to interpret directionality quickly and more accurate when the ring was used compared to a traditional drone. Best results were achieved using gaze, blinker and thruster models.

C. REMOTE COMMUNICATION

Humans can interact with drones in a collocated space, or remotely. Remote interaction requires a wireless communication link between the human and the system, such as a direct radio-frequency link. More recently, drones are now capable of carrying modems and connecting to internet networks such as 5G, which allows humans to interact with their drones from anywhere using a reliable and low-latency network, if there is signal coverage. These capabilities expand the spectrum of applications in which drones can be used. As an example, it allows drones to be used in package delivery systems such as described in [14], [15]. Additionally, drones can be used as a network station themselves, allowing for an ultra-flexible and cost-effective approach to provide wireless services [61], [62]. Internet connection for drones also benefits the creation of drone swarms, as it provides an easy way to create a network for drone communication.

Such connectivity allows flights beyond-line-of-sight (BLOS), which also presents certain disadvantages, especially on safety and security aspects. In most countries, BLOS flights are not permitted without previous authorizations, mainly due to safety risks (e.g. crashes with manned aircraft). Additionally, longer-range flights increase the chance of physical (e.g. firearm shots) and cyber (e.g. signal jamming) attacks. For example in [63], the authors discuss cyber-physical attacks on drone delivery systems, in which the vendor wants to deliver a package in the shortest possible time while an attacker wants to cause delays.

D. EMOTION ENCODING

Emotion encoding in robots can be beneficial as it increases social interaction and enhances communication; equivalently to how humans perceive dog happiness when they wag their tails. Drones lack humanoid characteristics such as a torso, legs, and arms; therefore, emotion encoding must be made through a combination of movement parameters, such as velocity, acceleration, and trajectory [64]. A previous study encoded emotion in a drone prototype and a user study was conducted to discover if users could read the robot emotion [66]. The authors first elicited 8 stereotypes of personality and their respective emotion characteristics (brave, dopey/sleep, grumpy, happy, sad, scared, shy). For each stereotype, a drone interaction profile was created, listing characteristics such as fast vs slow, instant vs delayed, gentle vs powerful and so on. Taking the stereotypes and profiles into consideration the authors merged some similar characteristics and created four emotion profiles for drones: exhausted, anti-social, adventurer hero, sneaky-spy (not implemented in the user study). For each of the three profiles implemented the flight characteristics were adjusted accordingly to: speed, reaction time, altitude, and special movements (flip, starts and stops, wobbles). Participants were asked to observe the drone and answer a questionnaire with the emotional state they believed the drone to be. Results demonstrated that emotion was correctly recognized 60% of the time when using a single keyword (exhausted, anti-social, adventurer) and 85% when a second keyword was used (sleepy, sad, grumpy and so on).

Previous research aimed to investigate the impact of encoding emotional states in drones, and how it influences user emotion [66]. The authors 3D printed a prototype named Daedalus, which is capable of head movement (pitch and roll) as well as changing eye colors (white and red). Four expressions were pre-programmed into Daedalus: (1) head roll with white eyes and propeller off, (2) head pitch with white eyes and propeller off, (3) head roll with white eyes and propeller on, (4) head pitch with red eyes and propeller on. An experiment was performed with 30 students; each participant would stay 0.5-0.7 meters away from the drone and observe while it performed one of the pre-programmed actions. After observing Daedalus, the participants had to answer (1) what do you feel? and (2) what do you think the robot is feeling? by selecting one of 7 cards (happiness, sadness, anger, fear, disgust, surprise and contempt). Results demonstrated that positive expressions were perceived with the propellers off (happiness and surprise), but the opposite was found with operating propellers (mostly fear and anger). It was also found that red eyes (4th movement) were highly impacted participants as 50% selected they were in fear, and 80% selected that the robot was angry. Results achieved in these studies demonstrate the potential of emotion encoding to provide a richer human-drone interaction experience.

VI. INNOVATIVE PROTOTYPES AND USE CASES

Drones are currently being used for a broad range of applications, but researchers are further exploring new ways in which these systems can be useful. This section presents novel drone prototypes and envisioned use cases. Prototypes with similar purposes were aggregated in categories, which are discussed in the following sub-sections.

A. FLYING USER INTERFACES

This sub-section presents drone prototypes designed to enhance and add mobility to user interfaces. Drone's ability to fly in a 3D space allows it to position itself anywhere around the user at any orientation. This fact can be explored to augment user interfaces as drones can be used as a new medium for both input and output of information [13]. Researchers have previously classified the phases of flying interfaces into three categories: approaching the user, interaction, and leaving phase; which can be used to call its attention [67]. These systems can be used for controlling crowds during emergency situations, provide feedback and guidance to athletes during sports, or even act as a tour-guide to outdoors activities [68], [69].

Previous work explored the use of two drones as flying displays, one carrying a projector while another carries a projection screen [67]. This approach can be used as a new model for public display in urban environments as it allows the display to grab attention by approaching the user, interacting and leaving. A prototype using two Parrot ARDrones with a modified stabilization algorithm was built and evaluated. The relation between the drones was based on a master-slave relationship, the projector drone follows the path from the screen drone using visual markers and computer vision to position itself to display the image properly. The first experiment compared the modified drone's ability to hover in place against a non-modified version. The prototype was able to hover significantly more accurate than the non-modified drone ($p < 0.05$; Wilcoxon Rank test) even though they were carrying heavier payloads (screen and projector). The second experiment compared the projection accuracy when using/not using visual markers for localization. The system with a visual marker achieved significantly higher accuracy ($p < 0.05$; Fisher's exact test). The prototype was used during a research forum in Tokyo as a demonstration and successfully caught the attendee's attention.

A custom-built octocopter carrying a smartphone and video projector was successfully used to display images and SMS texts on arbitrary surfaces [70]. For evaluation purposes, a flying experiment was performed outdoors displaying the received messages on a building wall. The flight lasted 7 minutes and approximately 40 people were standing 15 meters away. During the experiment, a total of 23 messages were displayed and at the end 14 participants provided feedback during an interview. Users found the system to be a fun experience capable of grabbing attention and envisioned use-cases such as interactive storytelling and advertisement applications.

In [71] the authors describe two flying display prototypes designed for both indoors and outdoors interaction. The first prototype is meant to be used indoors and it consists of adding both a screen and a mobile projector to the same drone. This system was tested during a banquet (200 persons) and an exhibition opening (30 persons) where participants were able to text a message to be displayed on the drone while it hovered around the location. The results were positive as participants engaged in social interaction as a group, every text displayed on the drone made participants shout, laugh and clap. The second prototype is another example where two drones are used outdoors for carrying a projector and a screen canvas, the system was tested but there was no user study performed. This set-up allows for outdoor projection only during nights due to illumination constraints.

A device with a stronger illumination screen such as an iPad can also be attached to drones to mitigate the issue of illumination and allow indoor use during daylight [68], [69]. In this project, an iPad was attached to an octocopter. A demonstration was performed to 12 users. Feedback acquired through interviews and questionnaires stated large potential for the application [69]. A reading test was performed to evaluate how the motion of the display would affect reading performance [68]. In this experiment, twelve participants had to read characters from the screen during 4 different occasions: (1) system sitting on a table, (2) hovering, (3) flying pass by the user, (4) user walking behind the moving display at a constant speed. Results showed a significantly less reading accuracy when both the user and displays are moving (case 4) and did not show a significant difference between cases 1, 2 and 3. The authors conclude that when both display and users are in motion the font or content size should be increased.

B. SOCIAL COMPANIONS

This section discusses drone prototypes that explore social interactions with users. Exercising bring many health benefits for humans and technology has been previously used to enhance jogging experience, for example as in mobile applications and sports watches. Previous work has explored the use of quad-copters as a jogging companion, and the prototype was named Joggobot [16]. While existing systems focus on keeping track and enhancing the performance of the runner, the authors of Joggobot focused on enhancing the social aspects of jogging. The prototype was built with the Parrot ARDrone, which takes-off and flies 3 meters ahead of the runner; the prototype can only accompany a user in a straight-line and the user must wear a t-shirt with a visual marker allowing the drone to easily locate itself in respect of the user. There was no formal evaluation of the system but preliminary insights by users who tried it demonstrated positive feedback towards the concept. Users noted that the system helped distract them from exhaustion and challenged to increase efforts. Some users preferred Joggobot to follow the user pace and guidance, while some users liked the idea of the robot being in control of the pace as it can motivate and compel users to follow it. Users also expressed a need for means to communicate with the robot, and the authors suggested using heart rate monitoring as an implicit communication tool as Joggobot could pace the jogging according to health recommendations.

A technical specification of a custom-built quad-copter designed to be a jogging companion is provided in [72]. The authors tested 6 different custom design to achieve a configuration that best compromise between performance, safety, and stability for outdoor flying. The final design consists of: a Safeflight Quadcopter 500mm frame, GemFan 10inch propellers, Sunnysky x2212 980kv brushless motors, a pixhawk flight controller, uBlox GPS, and HMC5883 magnetometer and a 915MHz telemetry link, the prototype is controlled through the APM Planner control ground station.

Drones can also be used as companions for visually impaired persons to provide navigation assistance [73]. This study envisions a drone system that stands-by on a wearable bracelet until its assistance is required. A blind user would command the drone to a destination using voice commands, and the drone would provide guidance until the target is reached. The user could follow the drone through the auditory feedback provided by the noise of the spinning propellers. Once a command is received, the drone calculates the distance to the target location and guides the user flying at a set distance ahead avoiding obstacles. A Bluetooth connection to the bracelet would allow the drone to adapt its distance and speed relative to the user. The two envisioned use cases are to guide users to a specific location or to assist in finding misplaced objects using computer vision algorithms. Although the system is not yet developed, a preliminary study was performed with a blind user and a Wizard of Oz approach to control a miniature drone. The participant was able to successfully follow the drone as envisioned and provided positive feedback about the project idea.

Researchers also envisioned the use of drones as an agent to support a clean environment [74]. In this application, the drone would find trash items on the floor, persuade users to pick it up and guide them to the nearest trash bin. To simulate the system behavior a researcher controlled a Parrot ARdrone through a smart-phone application while being recorded. The video was edited to add lighting effects, ambient street sounds, and motor noise. Three videos were created, and the drone had a different persuasion technique on each: visual, audio, and a combination of both. An online between-subject study with 82 participants was performed; each participant watched one of the videos and filled out a survey afterward. Although results analysis did not find an effect of the interaction modality (visual, audio, both) on user's compliance, other factors were observed. Females participants perceived the drone as friendlier than males. Also, participants from developing countries rated the perceived persuasion, compliance, pleasantness, and sensibility of the drone significantly higher than participants from developed countries, suggesting that cultural factors impact human-drone interaction.

C. ARTS AND SPORTS

This section presents how drones can be used to create artwork and new sports. Drawing on landscaping always raised interest among people and as drones become popular more people will be able to watch landscapes from the sky [75]. To create art pieces in a landscape requires a large amount of planning and time used to require planning and time, but with the use of drones, it can be an easy and fast task. An approach to quickly create landscape art is described in [75] as follows: a user can draw a sketch on a mobile phone screen that displays the video stream from a drone camera. The user than flies the drone above the area where the work will be created. While the drone hovers above the area, the user follows the screen drawing by walking and putting markers on the ground. At this point the user can land the drone and mow the grass following the previously marked points, creating the landscape work. Using this approach and a commercial-off-the-shelf drone, a user was able to create by himself a large smiley face on a grass field in less than 30 minutes, two trees were incorporated in the drawing like the eyes of the smiley face.

Technology can be used to assist sports as referee's tools for instant replay or to augment the entertainment, but drones can take such capabilities even further. A project known as HoverBall envisions augmenting sports by utilizing a drone as a ball capable of changing its physics dynamics [76]. The drone is enclosed in a circular cage and can change physics dynamics such as gravity, speed, and trajectory of the ball. Hoverball allows the design of new sports and modification of current sports to enhance player experience. As an example, Hoverball could decrease the speed of the ball or gravity effect during a Volleyball game to allow unskilled players or even kids and the elderly to play the game. Such a system could be used to create games that take into consideration players skill and adapt the difficulty to allow skilled and unskilled users to play together. An initial HoverBall prototype was built using a Crazyflie nano-quadcopter enclosed in a Styrofoam grid shell and an Optitrack s250e motion tracking system. The initial version allows three simple throw interactions: hover, glide, and boomerang; but there was no formal evaluation of the system. The authors concluded that drones have the potential to augment sports, but research is necessary to deal with some current constraints, such as payload requirements to build a strong cage capable of absorbing impacts and increased flight time.

D. HAPTIC FEEDBACK FOR VIRTUAL REALITY

This section presents two projects where drones were used to create haptic feedback for virtual reality (VR) systems. Current VR systems can provide immersive visual and sound experiences, but it lacks the ability to provide tactile feedback. As drones can fly in a 3D space, they can be used to provide tactile feedback by touching the user at any location and speed to provide adequate experience. Small quad-copters have been used to provide haptic feedback for virtual reality games [77]. In this project, small drones are used to fly into users at varying speeds while they are immersed in a virtual environment system. To provide safety to participants the drone has a protective cage, therefore, the spinning propellers cannot hurt the user. The prototype was built using a Parrot Rolling Spider drone, able to carry 10grams and accelerating up to 18km/h; the theoretical energy capable of impacting the user is 0.8125Joules, which presents no harm to the user. Different tips can be attached to the drone, depending on the virtual environment to provide adequate feedback. The first prototyped game consists of a Mayan city in the jungle, the drones provide feedback in three scenarios: acting as bumblebees that are attacking the user, arrows that are shot by creatures at the player, and bricks and woods falling in the user as the ruins collapse. In all scenarios, the small drones fly around with a specific tip and bounces at the user providing the tactile feedback. Until this point, there was no user study performed for this project.

Drones have also been used to provide encountered-type of haptic feedback [78]. In this study, a prototype was built by attaching a lightweight flat object to a quad-copter. While the user is immersed in a virtual environment, the drone position itself allowing the user to touch it using a grasping object to provide adequately haptic feedback. In this case, the user would use a wand to touch the flat object, which was a sheet of paper. Although the resistance force of the paper was not enough to be perceived when the drone is not in movement, the airflow created during flight pushes the paper creating a resistance force measured at 0.118N (+- 0.036N), which is enough to be perceived. An experiment with 4 participants was performed to test the system. All participants were able to feel the haptic feedback when immersed in the virtual environment. The experiment asked participants to draw a straight-line using the wand while immersed in the virtual environment. Results showed that participants were more accurate when haptic feedback was provided.

E. OTHER PROTOTYPES

The first project presented in this section uses a drone to record videos and display a realistic experience for sports spectators, the second project uses drones to stream in real-time a self-image to an athlete for training purposes, and lastly a project to augment humans' mobility and perceptibility is presented.

A project named Flying Eyes explored the use of drones to autonomously track humans in a 3D space with a specific camera path, to create a realistic experience for spectators [79]. Flying eyes is an alternative to the expensive and big systems used to record videos in 3D spaces, such as the cameras used in soccer games. The system uses an autonomous quad-copter that executes computer vision algorithms to track individuals and fly different paths controlling the camera position and orientation towards the target. For the initial prototype, the user must wear a distinct color which will be used by the computer vision algorithms for detection, tracking and distance estimation. The computer vision algorithms are executed on the ground station, which communicates with the drone over a WiFi connection. Flying eyes calculates the drone positioning and two different flight paths named tracking and circling. When tracking mode is used the system follows the target and captures the image from behind. Circling mode differs because the drone flies in a circular path around the subject getting a different image perspective. The prototype was built using a Parrot ARDrone and tested with a single user, results suggest that a better mechanism is necessary to estimate the distance from the user. The authors plan to develop a second-generation prototype using a Mikrokopter model.

The mental image of one's self can help athletes to sharpen their skills and improve performance. Drones can be used as sports flying assistant by providing an athlete his external image through a head-mounted display or hand-held device [80]. The proposed system autonomously tracks the target athlete, commanding the camera angle and position. The athlete can see the image at a later moment (delayed), in real-time through a head-mounted display or through a hand-held device. and compute camera orientation. The speed, relative position to the user, and height of the drone can be controlled through a mobile application. The current prototype was built using a Parrot ARDrone and tested with a single user using both delayed and real-time video stream. Delayed video stream was tested with a soccer player and a user running upstairs; the current prototype was not fast enough to follow the user in the first case and did not provide adequate height control above the stairs, therefore further research would be required to select an appropriate drone for such uses. In real-time display mode, the system was successfully tested with a user swinging a baseball bat and a jogging activity while the image was displayed in a head-mounted display.

A research project named FlyingBuddy demonstrates how drones can be used to augment human mobility and perceptibility [73]. The prototype can fly manually or autonomously, and an iPhone was attached to the drone providing extra sensors and a communication link, a second iPhone is used as a client to control the system. The authors of FlyingBuddy elicited 4 different user scenarios for the system. The first scenario "flying to buy" allows the users to locate nearby stores, create a video-call with the salesman, and finally carry the product back to the buyer autonomously. Another scenario "flying to see" gives user abilities to explore and views beyond what they could see normally. The system could also be used to report automobile accidents, taking and sending pictures and precise locations to EMS allowing a better assessment of the situation and improving response time. Finally, FlyingBuddy can also be used as a mobile camera, taking pictures from different perspectives that we couldn't reach due to physical constraints. A prototype was built with a Parrot ARDrone, two iPhone 4, and custom-built software; but there was no user study performed with the prototype.

VII. CHALLENGES AND FUTURE WORK

Human-drone interaction is naturally limited by the challenges faced in general drone systems. For instance, safety is a major concern for both fields, as the fast-spinning propellers can cause damage and injuries in case of accidents. This constraint is especially important for collocated interaction. As previously discussed in this paper, recent drones and prototypes allow safe touch-interaction (due to measures such as propeller-guards). It is likely that this will become a trend and that future work in HDI will be done in the area of safe-to-touch drones. Another challenge caused by hardware limitation is short flight times. As discussed in Section 2, current drone models have flight times limited to 31minutes or less. However, this challenge cannot be easily be mitigated by HDI research as it is directly related to hardware and battery components. As research in related fields leads to longer flight times, HDI researchers will be able to design and study longer interactions. Similarly, as the payload capabilities of drones increase due to hardware advancements, they will be able to carry more sensors and actuators, which will also allow HDI researchers to design new systems and interactions.

An important sub-field of human-drone interaction is the study of control modalities used to send commands to the drone, which can be a challenging task to the user. Controlling a drone safely and accurately might require long training periods and dedication. This paper reviews the research performed to create natural user interfaces such as gesture, speech, touch, and others. Although the majority of current HDI papers focus on control modalities, further research would still be beneficial as we believe this field is crucial to enhance human-drone interaction. Control modalities are the direct interface between the user and the drone, and improvements in such a link can lead to more accurate control and decrease training periods. Additionally, control modalities have the potential to decrease the pilot workload, possibly leading to a decrease in accidents and safer systems. It is expected that as researchers better understand HDI and with advancements in hardware technologies, they will be able to improve current control modalities and find new ones.

Drones are likely to become ubiquitous to society, especially as they start to be used in a broader application spectrum. The prototypes reviewed in this paper demonstrated that their usage goes far beyond traditional uses such as photography and inspection. Additionally, to HDI research leading to new uses, it is also worth mentioning that advancements in hardware and software technology will allow drones to be used on applications not yet envisioned. In the near future, drones will be extensively used in the fields of public advertising, deliveries, sports entertainment, emergency response, and to augment human capabilities. Furthermore, drone's popularity will increase once we better understand how society accepts these systems, therefore, future researchers could contribute by studying how societies and different cultures view drones. Future work can be done to elicit design guidelines to ensure that future drone technologies are well accepted by society.

This paper presents an analysis of which are the most common drone models used for research. Although models manufactured by DJI dominate the commercial market, they are not as common among researchers. Over half of the studies reviewed in this paper used the Parrot ARDrone, however, this model is already discontinued, therefore it is expected that its use on research will start to decrease. Therefore, it is likely that a new drone model will emerge as researchers first choice; at this point it is unclear if one of Parrot's new models will become such drone. The analysis suggests that there is a lack of a drone platform specifically designed for human-drone interaction research. Therefore, the future development of an open-source drone specifically designed for this HDI research would be a strong contribution to the field. This platform would serve as a standard research tool, and it would allow researchers to easily integrate their own work and research.

VIII. CONCLUSION

As drones shifted from military technologies to the civilian world, they are now used in a wide variety of applications. As drone technology matures, these systems are becoming cheaper, easier to operate, and popular among a large number of users. Drone usage is expected to keep growing, and it is likely that such systems will become ubiquitous to society. Therefore, it is important to study the field of human-drone interaction to understand how users interact with these systems. This paper defines the field of human-drone interaction using an analogy to the well-established field of human-robot interaction. Proceeding, it presents the first comprehensive survey on the emerging field of human-drone interaction.

This survey presents a comparison of modern commercial-off-the-shelf multi-rotor drones, providing readers with both the maximum specifications and limitations of current drone models. Additionally, it presents a comparison of which models are mostly used by end-users versus models used by researchers. It is also discussed how HDI research evolved over the past years and what is the current state-of-the-art in the field. Traditionally drones were controlled using either a joystick, a ground control station, or a smartphone application; however, research in HDI led to new natural user interfaces such as gesture-based control, brain-computer interfaces, speech, and others. Research in HDI goes beyond control modalities only, this paper also covers additional aspects of human-drone interaction, including a review of proxemics studies, and emotion encoding in drones. Furthermore, innovative prototypes found in literature and envisioned use-cases are also presented, which allows us to envision future drone applications and HDI directions. Lastly, this paper presents a discussion on the current challenges and expectations for future research in the field of HDI.

Concluding, human-drone interaction is an emerging field that it is likely to keep growing. This survey shows that the state-of-the-art research consists mainly of evaluating and developing new control modalities, designing new applications where humans interact with drones, and enhancing such interaction by understanding how humans perceive the interaction (i.e. comfortable distances, communication). This paper serves both as a survey in the field of human-drone interaction, and as an introduction to researchers who would like to contribute to the field.

REFERENCES

[1] Federal Aviation Administration. (Jan. 2019). *Unmanned Aircraft Systems Forecast*. [Online]. Available: https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/Unmanned_Aircraft_Systems.pdf
[2] J. C. van Gemert, C. R. Verschoor, P. Mettes, K. Epema, L. P. Koh, and S. Wich, "Nature conservation drones for automatic localization and counting of animals," in *Proc. Workshop Eur. Conf. Comput. Vis.* Cham, Switzerland: Springer, 2014, pp. 255–270.
[3] L. Apvrille, T. Tanzi, and J.-L. Dugelay, "Autonomous drones for assisting rescue services within the context of natural disasters," in *Proc. 31st URSI IEEE Gen. Assembly Sci. Symp. (URSI GASS)*, Aug. 2014, pp. 1–4.
[4] P. Doherty and P. Rudol, "A UAV search and rescue scenario with human body detection and geolocalization," in *Proc. Australas. Joint Conf. Artif. Intell.* Berlin, Germany: Springer, 2007, pp. 1–13.
[5] M. Manimaraboopathy, H. S. Christopher, and S. Vignesh, "Unmanned fire extinguisher using quadcopter," *Int. J. Smart Sens. Intell. Syst.*, vol. 10, pp. 471–481, Sep. 2017.
[6] M. Goodrich and A. Schultz, "Human-robot interaction: A survey," *Found. Trends Human Comput. Interaction*, vol. 1, no. 3, pp. 203–275, 2008.
[7] I. Leite, C. Martinho, and A. Paiva, "Social robots for long-term interaction: A survey," *Int. J. Social Robot.*, vol. 5, no. 2, pp. 291–308, 2013.
[8] D. Tezza. (2019). *Fundamentals of Multi-Rotor Drones*. Accessed: Aug. 25, 2019. [Online]. Available: https://medium.com/@dantetezza/fundamentals-of-multi-rotor-drones-979c579ba960?sk=76a4874a6a5234905fedee6b69a4ab6a
[9] D. Gettinger and A. H. Michel, "Drone registrations, a preliminary analysis," Center Study Drone Bard College, Annandale-on-Hudson, NY, USA, Tech. Rep., Nov. 2017. [Online]. Available: http://dronecenter.bard.edu/drone-registration
[10] A. Fitzpatrick, "Drones are here to stay. Get used to it," *Time USA*, May 31, 2018. [Online]. Available: https://time.com/longform/time-the-drone-age/
[11] Federal Aviation Administration. (Jan. 2019). *Yearly Aircraft Registration Database*. [Online]. Available: https://www.faa.gov/licenses_certificates/aircraft_certification/aircraft_registry/releasable_aircraft_download/
[12] T. Krajník, V. Vonásek, D. Fišer, and J. Faigl, "AR-drone as a platform for robotic research and education," in *Proc. Int. Conf. Res.*, 2011, pp. 172–186.
[13] M. Funk, "Human-drone interaction: Let's get ready for flying user interfaces!" *Interactions*, vol. 25, no. 3, pp. 78–81, 2018.
[14] M. McFarland, "Google drones will deliver Chipotle burritos at Virginia Tech," CNN Money, Sep. 2016.
[15] Amazon. (2016). *Amazon Prime Air*. [Online]. Available: https://www.amazon.com/b?node=8037720011
[16] E. Graether and F. Mueller, "Joggobot: A flying robot as jogging companion," in *Proc. ACM CHI Extended Abstr. Hum. Factors Comput. Syst.*, 2012, pp. 1063–1066.
[17] E. Peshkova, M. Hitz, and B. Kaufmann, "Natural interaction techniques for an unmanned aerial vehicle system," *IEEE Pervasive Comput.*, vol. 16, no. 1, pp. 34–42, Jan./Mar. 2017.
[18] J. R. Cauchard, K. Y. Zhai, and J. A. Landay, "Drone & me: An exploration into natural human-drone interaction," in *Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput.*, 2015, pp. 361–365.
[19] J. A. Landay, L. E. Jane, L. E. Ilene, and J. R. Cauchard, "Drone & Wo: Cultural influences on human-drone interaction techniques," in *Proc. ACM CHI Conf. Hum. Factors Comput. Syst.*, 2017, pp. 6794–6799.
[20] P. Abtahi, D. Y. Zhao, L. E. Jane, and J. A. Landay, "Drone near me: Exploring touch-based human-drone interaction," *Proc. ACM Interact., Mobile, Wearable Ubiquitous Technol.*, vol. 1, no. 3, p. 34, 2017.
[21] W. S. Ng and E. Sharlin, "Collocated interaction with flying robots," in *Proc. IEEE RO-MAN*, Jul./Aug. 2011, pp. 143–149.

[22] A. Mashood, H. Noura, I. Jawhar, and N. Mohamed, "A gesture based kinect for quadrotor control," in *Proc. IEEE Int. Conf. Inf. Commun. Technol. Res. (ICTRC)*, May 2015, pp. 298–301.

[23] A. Sanna, F. Lamberti, G. Paravati, and F. Manuri, "A kinect-based natural interface for quadrotor control," *Entertainment Comput.*, vol. 4, no. 3, pp. 179–186, 2013.

[24] M. Chilmonczyk, "Kinect control of a quadrotor UAV," Univ. South Florida, Tampa, FL, USA, Tech. Rep., Apr. 2014.

[25] K. Ikeuchi, T. Otsuka, A. Yoshii, M. Sakamoto, and T. Nakajima, "KinecDrone: Enhancing somatic sensation to fly in the sky with Kinect and AR.Drone," in *Proc. ACM 5th Augmented Hum. Int. Conf.*, 2014, Art. no. 53.

[26] A. Sarkar, K. A. Patel, R. K. G. Ram, and G. K. Capoor, "Gesture control of drone using a motion controller," in *Proc. IEEE Int. Conf. Ind. Inform. Comput. Syst. (CIICS)*, Mar. 2016. pp. 1–5.

[27] R. A. S. Fernández, J. L. Sanchez-Lopez, C. Sampedro, H. Bavle, M. Molina, and P. Campoy, "Natural user interfaces for human-drone multi-modal interaction," in *Proc. IEEE Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2016, pp. 1013–1022.

[28] A. Stoica, F. Salvioli, and C. Flowers, "Remote control of quadrotor teams, using hand gestures," in *Proc. ACM/IEEE Int. Conf. Hum.-Robot Interact.*, Mar. 2014, pp. 296–297.

[29] K. Miyoshi, R. Konomura, and K. Hori, "Above your hand: Direct and natural interaction with aerial robot," in *Proc. ACM SIGGRAPH Emerg. Technol.*, 2014, Art. no. 8.

[30] T. Sun, S. Nie, D.-Y. Yeung, and S. Shen, "Gesture-based piloting of an aerial robot using monocular vision," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May/Jun. 2017, pp. 5913–5920.

[31] J. Nagi, A. Giusti, G. A. Di Caro, and L. M. Gambardella, "Human control of UAVs using face pose estimates and hand gestures," in *Proc. ACM/IEEE Int. Conf. Hum.-Robot Interact.*, Mar. 2014, pp. 252–253.

[32] V. M. Monajjemi, J. Wawerla, R. Vaughan, and G. Mori, "HRI in the sky: Creating and commanding teams of UAVs with a vision-mediated gestural interface," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Nov. 2013, pp. 617–623.

[33] I. Maza, F. Caballero, R. Molina, N. Peña, and A. Ollero, "Multimodal interface technologies for UAV ground control stations," in *Proc. 2nd Int. Symp. UAVs*, Reno, NV, USA. Dordrecht, The Netherlands: Springer, Jun. 2009, pp. 371–391.

[34] K. Miyoshi, R. Konomura, and K. Hori, "Entertainment multi-rotor robot that realises direct and multimodal interaction," in *Proc. 28th Int. BCS Hum. Comput. Interact. Conf. HCI, Sand, Sea Sky-Holiday (HCI)*, 2014, pp. 218–221.

[35] K. LaFleur, K. Cassady, A. Doud, K. Shades, E. Rogin, and B. He, "Quadcopter control in three-dimensional space using a noninvasive motor imagery-based brain-computer interface," *J. Neural Eng.*, vol. 10, no. 4, Aug. 2013, Art. no. 046003.

[36] F. Tepper. (2016). *University of Florida Held the World's First Brain-Controlled Drone Race-TechCrunch*. Accessed: Aug. 24, 2019. [Online]. Available: https://techcrunch.com/2016/04/25/university-of-florida-held-the-worlds-first-brain-controlled-drone-race/

[37] AUVSI News. (2019). *University of South Florida's Brain-Drone Race Welcomes Diversity and Inclusivity*. Accessed: Aug. 24, 2019. [Online]. Available: https://www.auvsi.org/industry-news/university-south-floridas-brain-drone-race-welcomes-diversity-and-inclusivity/

[38] D. Taylor. (2019). *UA Students Combine Computer Science, the Brain to Fly Drones.-Tuscaloosa News*. Accessed: Aug. 24, 2019. [Online]. Available: https://www.tuscaloosanews.com/news/20190405/ua-students-combine-computer-science-brain-to-fly-drones

[39] A. Nourmohammadi, M. Jafari, and T. O. Zander, "A survey on unmanned aerial vehicle remote control using brain–computer interface," *IEEE Trans. Human-Mach. Syst.*, vol. 48, no. 4, pp. 337–348, Aug. 2018.

[40] N. Kos'myna, F. Tarpin-Bernard, and B. Rivet, "Bidirectional feedback in motor imagery BCIs: Learn to control a drone within 5 minutes," in *Proc. ACM CHI Extended Abstracts Hum. Factors Comput. Syst.*, 2014, pp. 479–482.

[41] N. Kosmyna, F. Tarpin-Bernard, and B. Rivet, "Drone, your brain, ring course: Accept the challenge and prevail!" in *Proc. ACM Int Joint Conf Pervasive Ubiquitous Comput., Adjunct Publication*, 2014, pp. 243–246.

[42] N. KosMyna, F. Tarpin-Bernard, and B. Rivet, "Towards brain computer interfaces for recreational activities: Piloting a drone," in *Human-Computer Interaction—INTERACT*. Berlin, Germany: Springer-Verlag, 2015, pp. 506–925.

[43] B. H. Kim, M. Kim, and S. Jo, "Quadcopter flight control using a low-cost hybrid interface with EEG-based classification and eye tracking," *Comput. Biol. Med.*, vol. 51, pp. 82–92, Aug. 2014.

[44] T. Shi, H. Wang, and C. Zhang, "Brain Computer Interface system based on indoor semi-autonomous navigation and motor imagery for Unmanned Aerial Vehicle control," *Expert Syst. Appl.*, vol. 42, no. 9, pp. 4196–4206, 2015.

[45] J. F. B. Coenen, "UAV BCI Comparison of manual and pedal control systems for 2D flight performance of users with simultaneous BCI control," Ph.D. dissertation, Fac. Social Sci., Radboud Univ., Nijmegen, The Netherlands, Jun. 2015.

[46] M. J. Khan, K.-S. Hong, N. Naseer, and M. R. Bhutta, "Hybrid EEG-NIRS based BCI for quadcopter control," in *Proc. 54th Annu. Conf. Soc. Instrum. Control Eng. Jpn. (SICE)*, Hangzhou, China, 2015, pp. 1177–1182.

[47] J.-S. Lin and Z.-Y. Jiang, "Implementing remote presence using quadcopter control by a non-invasive BCI device," *Comput. Sci. Inf. Technol.*, vol. 3, no. 4, pp. 122–126, 2015.

[48] D. Zhang and M. M. Jackson, "Quadcopter navigation using Google Glass and brain-computer interface," M.S. thesis, Georgia Inst. Technol., Atlanta, GA, USA, 2015.

[49] D. Tezza, S. Garcia, T. Hossain, and M. Andujar, "Brain eRacing: An exploratory study on virtual brain-controlled drones," in *Virtual, Augmented and Mixed Reality. Applications and Case Studies* (Lecture Notes in Computer Science), vol. 11575, J. Chen and G. Fragomeni, Eds. Cham, Switzerland: Springer, 2019, pp. 150–162.

[50] G. Jones, N. Berthouze, R. Bielski, and S. Julier, "Towards a situated, multimodal interface for multiple UAV control," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2010, pp. 1739–1744.

[51] J. P. Hansen, A. Alapetite, I. S. MacKenzie, and E. Møllenbach, "The use of gaze to control drones," in *Proc. ACM Symp. Eye Tracking Res. Appl.*, 2014, pp. 27–34.

[52] K. Higuchi and J. Rekimoto, "Flying head: A head motion synchronization mechanism for unmanned aerial vehicle control," in *Proc. ACM CHI Extended Abstracts Hum. Factors Comput. Syst.*, 2013, pp. 2029–2038.

[53] K. Higuchi, K. Fujii, and J. Rekimoto, "Flying head: A head-synchronization mechanism for flying telepresence," in *Proc. IEEE 23rd Int. Conf. Artif. Reality Tele-Existence (ICAT)*, 2013, pp. 28–34.

[54] H. Hayakawa, C. L. Fernando, M. H. D. Saraiji, K. Minamizawa, and S. Tachi, "Telexistence drone: Design of a flight telexistence system for immersive aerial sports experience," in *Proc. ACM 6th Augmented Hum. Int. Conf.*, 2015, pp. 171–172.

[55] N. Li, S. Cartwright, A. S. Nittala, E. Sharlin, and M. C. Sousa, "Flying frustum: A spatial interface for enhancing human-UAV awareness," in *Proc. ACM 3rd Int. Conf. Hum.-Agent Interact.*, 2015, pp. 27–31.

[56] A. Yeh, P. Ratsamee, K. Kiyokawa, Y. Uranishi, T. Mashita, H. Takemura, M. Fjeld, and M. Obaid, "Exploring proxemics for human-drone interaction," in *Proc. ACM 5th Int. Conf. Hum. Agent Interact.*, 2017, pp. 81–88.

[57] B. A. Duncan and R. R. Murphy, "Comfortable approach distance with small unmanned aerial vehicles," in *Proc. IEEE RO-MAN*, Aug. 2013, pp. 786–792.

[58] W. Jensen, S. Hansen, and H. Knoche, "Knowing you, seeing me: Investigating user preferences in drone-human acknowledgement," in *Proc. ACM CHI Conf. Hum. Factors Comput. Syst.*, 2018, Art. no. 365.

[59] D. Szafir, B. Mutlu, and T. Fong, "Communication of intent in assistive free flyers," in *Proc. ACM/IEEE Int. Conf. Hum.-Robot Interact.*, Mar. 2014, pp. 358–365.

[60] D. Szafir, B. Mutlu, and T. Fong, "Communicating directionality in flying robots," in *Proc. 10th Annu. ACM/IEEE Int. Conf. Hum.-Robot Interact.*, 2015, pp. 19–26.

[61] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 3949–3963, Jun. 2016.

[62] M. Mozaffari, A. T. Z. Kasgari, W. Saad, M. Bennis, and M. Debbah, "Beyond 5G with UAVs: Foundations of a 3D wireless cellular network," *IEEE Trans. Wireless Commun.*, vol. 18, no. 1, pp. 357–372, Jan. 2019.

[63] A. Sanjab, W. Saad, and T. Başar, "Prospect theory for enhanced cyber-physical security of drone delivery systems: A network interdiction game," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Paris, France, May 2017, pp. 1–6.

[64] C. Hieida, H. Matsuda, S. Kudoh, and T. Suehiro, "Action elements of emotional body expressions for flying robots," in *Proc. 11th ACM/IEEE Int. Conf. Hum.-Robot Interact. (HRI)*, Mar. 2016, pp. 439–440.

[65] J. R. Cauchard, K. Y. Zhai, M. Spadafora, and J. A. Landay, "Emotion encoding in Human-Drone interaction," in *Proc. 11th ACM/IEEE Int. Conf. Hum.-Robot Interact. (HRI)*, Mar. 2016, pp. 263–270.
[66] D. Arroyo, C. Lucho, S. J. Roncal, and F. Cuellar, "Daedalus: A sUAV for human-robot interaction," in *Proc. ACM/IEEE Int. Conf. Hum.-Robot Interact.*, Mar. 2014, pp. 116–117.
[67] H. Nozaki, "Flying display: A movable display pairing projector and screen in the air," in *Proc. CHI Extended Abstr. Hum. Factors Comput. Syst.*, 2014, pp. 909–914.
[68] S. Schneegass, F. Alt, J. Scheible, and A. Schmidt, "Midair displays: Concept and first experiences with free-floating pervasive displays," in *Proc. ACM Int. Symp. Pervasive Displays*, 2014, Art. no. 27.
[69] S. Schneegass, F. Alt, J. Scheible, A. Schmidt, and H. Su, "Midair displays: Exploring the concept of free-floating public displays," in *Proc. CHI Extended Abstracts Hum. Factors Comput. Syst.*, 2014, pp. 2035–2040.
[70] J. Scheible, A. Hoth, J. Saal, and H. Su, "DisplayDrone: A flying robot based interactive display," in *Proc. 2nd ACM Int. Symp. Pervas. Displays*, 2013, pp. 49–54.
[71] J. Scheible and M. Funk, "*In-situ*-displaydrone: Facilitating co-located interactive experiences via a flying screen," in *Proc. 5th ACM Int. Symp. Pervas. Displays*, 2016, pp. 251–252.
[72] F. Mueller and M. Muirhead, "Understanding the design of a flying jogging companion," in *Proc. 27th Annu. ACM Symp. User Interface Softw. Technol.*, 2014, pp. 81–82.
[73] M. Avila, M. Funk, and N. Henze, "DroneNavigator: Using drones for navigating visually impaired persons," in *Proc. 17th Int. ACM SIGACCESS Conf. Comput. Accessibility*, 2015, pp. 327–328.
[74] M. Obaid, O. Mubin, C. A. Basedow, A. A. Ünlüer, M. J. Bergström, and M. Fjeld, "A drone agent to support a clean environment," in *Proc. ACM 3rd Int. Conf. Hum.-Agent Interact.*, 2015, pp. 55–61.
[75] J. Scheible and M. Funk, "DroneLandArt: Landscape as organic pervasive display," in *Proc. 5th ACM Int. Symp. Pervasive Displays*, 2016, pp. 255–256.
[76] K. Nitta, K. Higuchi, and J. Rekimoto, "HoverBall: Augmented sports with a flying ball," in *Proc. ACM 5th Augmented Hum. Int. Conf.*, 2014, Art. no. 13.
[77] P. Knierim, T. Kosch, V. Schwind, M. Funk, F. Kiss, S. Schneegass, and N. Henze, "Tactile drones—Providing immersive tactile feedback in virtual reality through quadcopters," in *Proc. ACM CHI Conf. Extended Abstracts Hum. Factors Comput. Syst.*, 2017, pp. 433–436.
[78] K. Yamaguchi, G. Kato, Y. Kuroda, K. Kiyokawa, and H. Takemura, "A non-grounded and encountered-type haptic display using a drone," in *Proc. ACM Symp. Spatial User Interact.*, 2016, pp. 43–46.
[79] K. Higuchi, T. Shimada, and J. Rekimoto, "Flying sports assistant: External visual imagery representation for sports training," in *Proc. ACM 2nd Augmented Hum. Int. Conf.*, 2011, Art. no. 7.
[80] D. He, H. Ren, W. Hua, G. Pan, S. Li, and Z. Wu, "FlyingBuddy: Augment human mobility and perceptibility," in *Proc. ACM 13th Int. Conf. Ubiquitous Comput.*, 2011, pp. 615–616.

DANTE TEZZA received the B.Sc. degree in computer engineering and the M.Sc. degree in software engineering from St. Mary's University, San Antonio, TX, USA. He is currently pursuing the Ph.D. degree with the Department of Computer Science and Engineering, University of South Florida, Tampa, FL, USA. He was with industry developing drone systems. He is currently a Research Assistant with the Neuro-Machine Interaction Laboratory, under the supervision of Dr. M. Andujar. His current research interests include drone technologies and human–drone interaction. In addition, during his M.Sc. program, he developed an Innovative Software Architecture that facilitates drone usage in STEM Education and Research.

MARVIN ANDUJAR received the Ph.D. degree in human-centered computing from the University of Florida, Gainesville, FL, USA. He is currently an Assistant Professor with the Department of Computer Science and Engineering, University of South Florida, Tampa, FL, USA. His current research interests include affective brain–computer interfaces where he focuses on measuring and decoding the user's affective state from the brain during human–machine interaction. He was recognized as a National Science Foundation Graduate Research Fellow, a GEM Fellow, a Generation's Google Scholar, and an Intel Scholar. His effort on brain–computer interfaces has led toward multiple publications in journals and conferences, obtain external funding of $300 000 from the CEO of Intel along with his colleagues, and co-founded the world's first Brain-Drone Race. The race was showcased in more than 550 news outlets, including *The New York Times*, Associated Press, Discovery Channel, The Verge, and Engadget.