CandyFly: Bringing fun to drone pilots with disabilities through adapted and adaptable interactions

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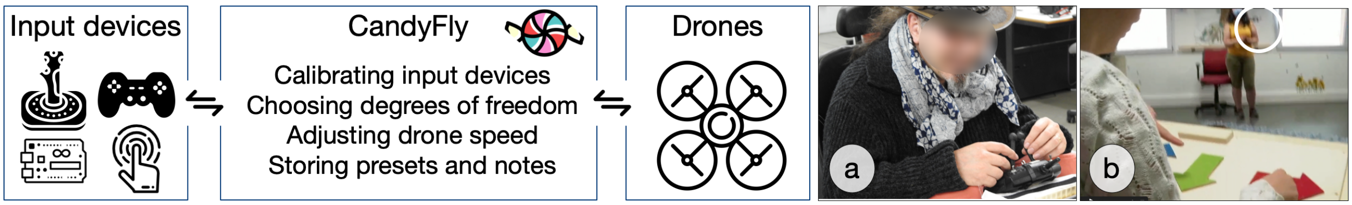

Figure 1: Left) CandyFly's architecture and main functionalities. a) P4 piloting with a conventional controller and extended sticks during the workshop 2. b) P1 flying with pressure sensitive arrows (drone circled in white) during workshop 7.

ABSTRACT

Flying drones is an increasingly popular activity. However, it is challenging due to the required perceptual and motor skills for following and stabilizing the drone, especially for people with special needs. This paper describes CandyFly, an application supporting people with diverse sensory, cognitive and motor impairments to pilot drones. We observed an existing accessible piloting workshop and evaluated CandyFly during eight additional workshops over three and a half years using a research-through-design process and ability-based design methods. We identified users' needs, formulated requirements and explored adaptive interactions such as using pressure-sensitive keys, adjusting controls to the pilots' range of motion, or limiting the drone's degrees of freedom to cope with a broad range of disabilities. Our results show that the pilots and their caregivers enjoyed flying and emphasized CandyFly's ability to be tailored to specific needs. Our findings offer a framework for designing adaptable systems and can support the design of future assistive and recreational systems.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility systems and tools**; **Interactive systems and tools**; **Empirical studies in accessibility**.

KEYWORDS

Drones, Human-Drone Interaction, Unmanned Aerial Vehicles, Piloting, Automation, Accessibility

1 INTRODUCTION

Drone piloting is gaining popularity in a recreational context thanks to many models available on the mass-market. Pilots use drones to take pictures, participate in races or just for the fun of flying. Within the field of Human-Computer Interaction, Human-Drone Interaction (HDI) is relatively recent, but is gaining more and more attention [8, 14, 45, 58]. It investigates diverse use cases such as navigation [10, 37], art [18, 55], or photography [16, 35], and it makes use of diverse interaction techniques, including for instance gestural and voice interaction [45, 58].

To operate a drone, pilots must handle take off, stabilize the drone by adjusting the power of the motors, follow trajectories by performing translations and rotations, and land the device on the ground. While performing these tasks, pilots must constantly monitor the drone's location in its environment, its speed and energy to avoid damage or accidents. These tasks require perceptual skills (perceiving distance, altitude, orientation) and motor skills (knowing how to move one's limbs and make precise movements) that make the activity fun but possibly too challenging for people with motor and cognitive impairments.

The goal of this work is to support people with disabilities to pilot drones as a leisure activity. Some associations such as "Illuminace" or the "têtes en l'air" [20] train people with mild motor impairments to fly and operate drones. However, people with disabilities also have a desire to participate in fun and enjoyable activities [42]. Leisure participation may also contribute to enhance the quality of life of people with impairments [5]. Yet, many activities for people with disabilities are aimed at rehabilitation or teaching, but relatively few at leisure activities.

In this paper we present our work for supporting drone pilots with diverse sensory, motor and cognitive impairments. More specifically, we have worked with eleven pilots with different types of impairments (including for instance attention and speech, motor movement or visual perception) and their caregivers over three years and half. This work was done in collaboration with Elheva [23], an association for people with impairments and the Artilect FabLab [3] who had already established a joint drone piloting workshop for people with diverse impairments. Both contacted us for help to design interaction techniques which were better adapted to users' needs. Indeed, during the existing piloting workshops participants were struggling to pilot and stabilize drones in the air, so the time actually spent flying was very short. To address this challenge, we followed a research-through-design process, in "an attempt to make the right thing: a product that transforms the world from its current state to a preferred state" [63].

We first present our research methodology that builds upon user-centered and ability-based [62] design techniques and its implementation in this work. We then describe the results of an initial observation study of an existing workshops from which we derived eight requirements to ground our work. Based on these, we introduce CandyFly (Figure 1), a software which is adaptable to the pilots' capabilities for piloting commercial drones with various input devices. We describe results of eight piloting workshops in which pilots with disabilities enjoyed flying different types of drones using CandyFly. Then, we describe an adaptation framework and formulate guidelines along hardware, software and automation to generalize our work. Finally, we discuss our work and propose directions to make our work relevant to people with other disabilities as well as to facilitate users' progression over time.

The contributions of our paper are threefold:

- The implementation of a research-through-design approach and ability-based design principles for the design of a system adaptable to people with a wide range of impairments and abilities.
- CandyFly, an application that allows people with impairments to pilot various commercial drones with different types of controllers that can be adapted to their abilities.
- An adaptation framework with guidelines covering hardware, software and automation adaptations for the development of future similar recreational systems.

2 RELATED WORK

This paper draws motivation from interaction for drone piloting in general, and accessible user interaction for enabling people with impairments to control (flying) robots more specifically.

2.1 Interactions for drone piloting

Commercially available drones are usually controlled via a radio controller, a tablet or smartphone app with touch controls or even a wireless gamepad [36]. Piloting a drone requires perceptual, motor and cognitive skills to get the drone up and running, stabilize it, move it and land it while monitoring it to avoid collisions and crashes. Drones without stabilization are especially difficult to fly. Pilots must constantly adjust the controls otherwise the drone may drift, stop or fall. The difficulty is part of the challenge which pilots of this type of drone seek to meet. For other uses, such as photography, drones often incorporate an autopilot that stabilizes the drone and allows them to be controlled by giving a speed command, rather than by adjusting motor power. With the autopilot, a drone flies almost by itself and if the user lets go of the controls, the drone will stay in place automatically. These models of drones are usually piloted by large radio controls or by applications on a tablet or a phone with a touch screen. Virtual or augmented reality headsets are also available to provide direct video feedback from the drone camera (First Person View or FPV). The use of FPV among drone pilots is particularly common for racing [56].

The work of the HCI and especially the HDI community has demonstrated that drones can be piloted with a wide variety of input devices and interaction techniques [58]. Some researchers suggest gestural interaction using hands [13, 15, 46, 47, 57], the whole body [49, 53, 54] or even the feet [15, 41]. Other interactions make use of Brain-Computer Interfaces (BCI) [48] for piloting drones without any physical controller or eye-tracking combined with a keyboard [32]. Other researchers have explored the approach of directly manipulating drones by touching, dragging or throwing them or by resizing sets of multiple drones [28]. Previous research mainly aimed at facilitating the command execution for drones rather than assisting people with special needs to progress.

2.2 Accessible interactions for robot control

Some prior research has investigated control interfaces for people with impairments, such as for interacting with robots or games. Plaisant et al. [51] designed a robot for pediatric rehabilitation which can be piloted using diverse sensors on the bodies of participants. Their study shows that it is better to use wireless interfaces, to integrate interfaces in pleasant objects such as bracelets and to add decoration which enhances the link with the robot (e.g. using the icon of a hand to indicate which part of the interface controls the robot's hand). Krishnaswamy and Kuber [38] have investigated the use of gestural interaction and BCI for robot piloting by people with motor impairments. While gestural interaction has become mainstream, BCI are today still limited to the use in laboratories.

In the context of drones as flying robots, PULSIT [61] proposes a glove that allows to pilot a drone and control its camera with a single hand. However, due to the complexity of commands the required cognitive and motor skills remain high and interaction might not be adequate for users with motor or cognitive impairments.

Drones have been explored for people with visual impairements, focusing on guidance and navigation tasks [4], to detect obstacles [30], to provide auditory feedback for blind runners [1] or to support orientation & mobility training [21, 29]. Gadiraju et al. [25] have shown that visually impaired people are interested in flying drones, including for leisure activities.

Recently, the Xbox Adaptive Controller has allowed gamers with impairments to use controllers which are accessible and adapted to personal needs and abilities [44]. This device provides real flexibility since each player can use it with its own preferred controllers. Even though this device is specifically made for video games, it could possibly be used in the context of controlling robots and drones. To our knowledge, there is no prior work on designing interaction techniques that are adaptable to diverse types of user needs for piloting drones.

3 METHOD

Designing accessible interactions and interfaces requires to involve people with disabilities [59] but also their family environment and their caregivers [7, 31]. Indeed, Phillips et Zhao [50] showed that people with special needs frequently abandon technology if their needs and opinions have not been considered in the design process.

To better understand the users' needs, evaluate the technology in a real context of use and iteratively create new ideas to support drone piloting, we decided to follow a process similar to technology probes [34], functional prototypes that can be used over long periods of time and have previously been used with people with impairments [24]. This is in line with research-through-design approaches which aim not only to produce usable artifacts, but also to generate knowledge through an active process of ideation, iteration and critique of potential solutions [63]. Similar approaches called

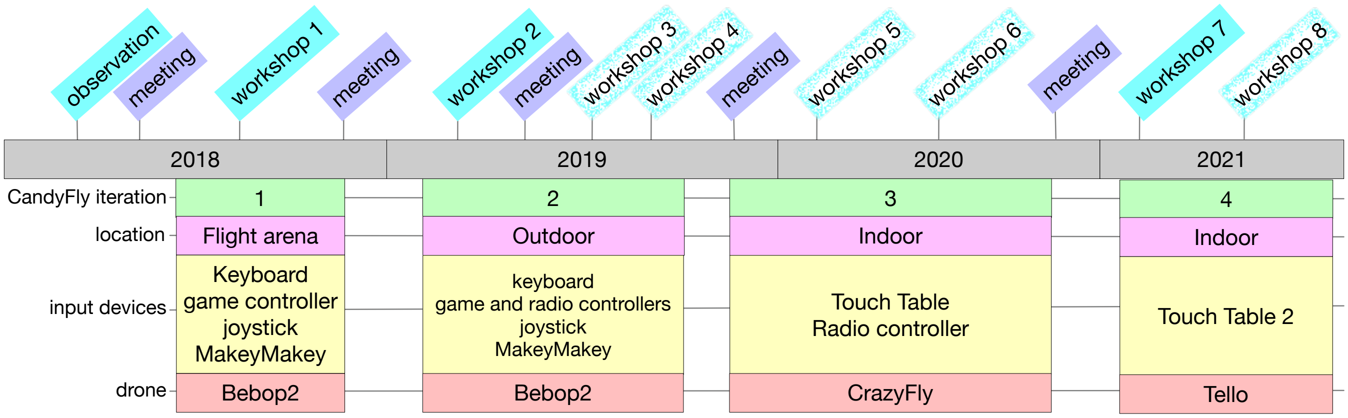

Figure 2: Chronological presentation of design steps and iterations. For each iteration, the flight location (pink), the control devices (yellow) and the drones (orange) are detailed. Workshops 3 to 6 and 8 took place using Candyfly as a technology probe.

ID	Gender	Age	Description	Workshops
P1	Female	12	Congenital motor and cognitive impairments, attention and speech disorders. Wheelchair user.	1 2 3 6 7
P2	Male	23	Congenital cognitive impairments. Limited attention span and 3D visual perception difficulties.	1
P3	Male	20	Congenital motor impairments in the hands and mild cognitive deficits. Experienced video game player.	1 2 3 5 7
P4	Male	45	Cognitive, speech and motor impairments following an accident. Wheelchair.	1 2 3 5
P5	Female	4	Congenital cognitive and motor impairments.	1
P6	Female	19	Lower body motor impairments and mild cognitive impairments.	5
P7	Male	9	Unspecified impairments.	6 8
P8	Female	15	Congenital cognitive, speech and motor impairments. Cerebral palsy. Wheelchair user.	6 8
P9	Male	> 65	Severe vision impairments.	7
P10	Male	20	Down's syndrome.	8
P11	Male	20	Autism.	8

Table 1: Pilots involved in the flying workshops. The age of the pilots is their age at the beginning of the workshop series.

"design after design" [9] and TechShops (collaborative workshop-based approaches) [7] have previously been applied for designing with people with cognitive and sensory impairments. We were also inspired by Metatla et al. [43] who proposed using highly adaptable technologies to assess the interactions and interfaces.

3.1 Participants

We had the opportunity to collaborate with the drone section of the Artilect Fablab which had been running accessible piloting workshops for a year with the Elheva association for people with disabilities. The organizing team consists of four volunteers from the drone section of the Fablab (O1, O2, O3, O4), an occupational therapist (T1) and a physical therapist (T2) who participated in all the workshops. The therapists provided a postural and cognitive framework adapted to the pilots by adding, for example, foam supports under the forearms or by adapting the room lighting.

Several pilots with different types of impairments participated in the workshops. The participants were chosen by the workshop organizers based on their availability but also on their cognitive and motor skills in order to explore how this activity can be part of physical training for different types of disabilities. The main purpose of the piloting workshop was to be a fun leisure activity for the participants, but it could also be integrated into their therapy. Table 1 gives a detailed description of the pilots involved throughout the project.

3.2 Procedure and data collection

Figure 2 summarizes the different activities performed including initial observation, meetings and workshops. It also shows the different iterations of CandyFly and details the specific input devices and drones used for each.

Initial Observation: Before designing new technologies, we wanted to better understand existing practices and challenges and formulate requirements to guide future design activities [40]. We started by observing five pilots, two therapists and the organizers during a half-day workshop and conducted interviews with the participants and their therapists T1 and T2 ("Observation" in Figure 2).

Iterative design and piloting workshops: We iteratively designed and assessed CandyFly during eight following workshops ("Workshop" in Figure 2). The workshops consisted of up to four hour sessions during which members of the Elheva association came to fly different types of drones. The CandyFly software went through four iterations. Between each, we met with the workshop organizers to review our interaction, gather feedback and discuss desirable changes. We applied principles of ability-based design [62] which strives to design versatile systems that adapt to diverse users by considering user abilities (and not disabilities) in the design process. The therapists that participated in the design were particularly helpful to carefully specify current and desirable abilities for our participants. From the second CandyFly iteration on, the prototype was left as a technology probe [34] with documentation to the workshop organizers so they configured and made use of the material on their own. We participated in workshops 1, 2 and 7 during which we helped the organizers to set up and interview the pilots. We filmed and photographed the workshops with the consent of the participants and their families. Workshops 3, 4, 5, 6 and 8 were held independently by the organizers. For Workshop 5 and 6, the organizers photographed parts of the sessions. For workshops 4, 5, 6 and 8 they provided written and oral feedback. Since many of our participants had cognitive impairments it was however not possible to conduct interviews [7] and sometimes companions or therapists helped us interpret their feedback.

4 OBSERVATIONAL STUDY RESULTS

In this section, we first describe our observations and then introduce the resulting requirements for the design of interactions to support drone piloting for people with various types of impairments.

The objective of the workshop was to provide a leisure drone piloting activity to people with various impairments. All pilots came to participate in a leisure activity that they expected to be "fun" (P2) and "like a video game" (P3).

We observed that all participants, except P3, had difficulty piloting the drone for more than a few seconds and regularly hit walls, the ceiling or lost it under furniture. This was mainly due to the difficulties in stabilizing the drone vertically as well as the high demand on cognitive and motor skills to control the precise movement. P3, who is an experienced video game player, succeeded in piloting the drone for a few minutes. Indeed, gaming may have provided him with similar competencies than piloting drones.

To improve the comfort and performance of the participants, the organizers and therapists had already made some material and contextual adaptations. For example, a height-adjustable table, forearm support wedges, or joysticks of different sizes for the remote controls (see Figure 3) were specifically made by T1. For each participant, the hardware configurations had to be memorized for reuse in subsequent workshops (e.g., noted on a sheet of paper). We present below our observations regarding cognition and perception as well as motor skills.

Cognition and perception: A quiet space was chosen for the workshop to avoid distractions and to make it easier for participants to focus. This is especially important because some of the participants have limited attention spans. For P1, all participants had to hide outside her field of vision so as not to distract her.

A challenge encountered by all participants involved piloting a drone in 3D with yaw (rotation around the vertical axis) which requires an egocentric and inverted orientation. This has caused many crashes and collisions of the drone. Also, when the drone moved too fast, some participants lost sight of it and could no longer control it.

Understanding the directions was a challenge for P1. To help her, another participant was placed in front of her, inside the flight space, while wearing colored stickers on her body that corresponded to colored stickers on the remote control. P2 had difficulty flying himself because he has no depth perception and thus only perceives visual 2D information. He wore virtual reality goggles with a first-person view while O2 piloted for him. He needed explanations by O1 and T1 at the beginning of each session to remember how the system works.

P1 and P4 used a wooden box (see Figure 3 a) that hid the complexity of the remote control and limited the ranges of the joysticks: vertical and horizontal movement only with a cross-shaped opening (i.e. no diagonal movements combining both changes in vertical and horizontal direction).

Motor skills: O2 and O3 built a table for P1 and P4 that can be adjusted to the height of their wheelchairs to support a comfortable arm position with foam support wedges (see Figure 3). A stand keeps the remote control in a comfortable position. P3 used a custom-made tablet hanging from his shoulders to put the remote control on and prevent wrist fatigue (Figure 3 b). All participants used the controller with longer sticks and/or with larger tips that were 3D printed for better grip. We observed that some participants made small but precise motor movements while others made larger, strong, and imprecise movements.

4.1 Identified requirements

Based on these results, we formulated a set of eight requirements. These requirements were consolidated and generalized with workshop organizers and therapists to cover different types of impairments.

Promote playfulness (FUN). Pilots should enjoy flying the drone freely, reaching specific places or performing various motions. The level of difficulty can be modulated so that it is sufficient to be challenging and rewarding but not excessive. Pilots can also progress over time and develop skills.

Support pilots' concentration (CONCENTRATION). Pilots with short attention spans need to be able to concentrate on flying. Distractions should be minimized.

Ensure safety of pilots, caregivers, and equipment (SAFETY). This involves reducing the risks in the air and on the ground that can occur during a technical failure or piloting error.

Adapt the flight domain to perceptual capacities (PERCEPTION). Situations where the drone leaves the pilot's field of vision because of its position (e.g. behind the person) or its speed of movement must be avoided.

Adapting devices and interactions to motor abilities (MOTOR). Pilots must be able to fly comfortably with movements that they are able to do without pain. Interactions must be adjustable to the strength and range of motion of the pilots.

Ease or automate the drone stabilization (STABILIZATION). Pilots need to be supported during delicate flight phases such as takeoff or

Figure 3: Participants piloting drones during a workshop, the drones are surrounded by white circles. a) P1 (cognitive and motor impairments) using an adjustable table and a wooden box to hide and direct the controller; b) P3 (mild motor impairments) with a controller resting on a tablet attached to the shoulders; c) P4 (motor impairments) with a controller resting on an inclined support and foams to support the forearms.

landing. If no controls are touched, the drone should hover without requiring continuous adjustment.

Maintain a causal relationship between controls and drone behavior (CAUSALITY). Pilots must feel in control of the drone to appreciate the activity. For example, the latency between the command and the drone reaction must be minimized.

Limit the complexity of commands and movements (COMPLEXITY). Pilots must be able to use simplified controls that are independent of each other (unlike joysticks that control two dimensions in parallel). Some movements causing difficulties like changing the orientation of the drone (yaw) must be limited.

5 CANDYFLY: AN ADAPTABLE APPLICATION

To meet the pilots' needs and explore solutions to the previously formulated requirements, we designed CandyFly, a software application that allows to adapt the degree of control to the users' abilities by taking advantage of the drones' autopilots and different input devices. Figure 1 illustrates the concept, architecture and main properties of CandyFly. All iterations of CandyFly were built in Python using the Qt5 library for the graphical user interface (GUI). The application can be used with various input devices and drones. For each iteration we tested different devices as detailed in Figure 2. We outline below the approaches chosen to tailor interactions to pilots' abilities and needs. We explicitly link these choices to the above mentioned requirements FUN, CONCENTRATION, SAFETY, PERCEPTION, MOTOR, STABILIZATION, CAUSALITY and COMPLEXITY (see section 4.1).

5.1 Adapting interactions to users' abilities: hardware, software and automation

Adapting the existing drone piloting systems to users' abilities [62] was a central design challenge in our work. We decided to work on three axes that constitute a drone piloting system: hardware, software and automation.

In terms of hardware, CandyFly allows pilots to choose among several types of commodity controllers such as radio controllers, gamepads, keyboards or makey makey [17] (a platform allowing to make objects conductive and use them as keyboard keys), in order to adapt to the physical abilities (MOTOR) of the user. We tested several of these devices in iterations 1 and 2. Pilots can also control the movement of the drone with tactile (iteration 2) or pressure-sensitive (iteration 3 and 4) keys embedded in a wooden table designed and built by the organizers as illustrated in Figure 4. Capacitive or pressure sensors under the keys transmit the values via an Arduino [2] connected to the application via USB. In the third iteration, we ensured that the pilots could control the movements in a continuous or discrete way in two directions, top/bottom and right/left (MOTOR, COMPLEXITY). In the continuous case, more pressure results in a higher speed instruction given to the drone. In the discrete case, the keys work like buttons, i.e. the command is carried out only when the button is released. In the fourth iteration, we used a new version of table featuring more degrees of freedom (front/back and clockwise/counter clockwise rotations) as well as audio and visual feedback when the pilots use the keys (FUN). Each direction is associated with an abstract sound and illumination of colored LEDs as illustrated in Figure 4.c. The sound amplitude and the LEDs blinking frequency increase with the pressure applied onto the keys (CAUSALITY). We also explored alternative interaction techniques such as raising a drone by shaking an object or spinning a wheel to test different types of motor movement. We used a BITalino R-IoT [52] device to retrieve accelerometers and gyroscope data. These interaction were implemented in Iteration 3 with adjustable gains and thresholds for the motion energy.

At the software level, we implemented a GUI that provides access to most adaptations. Figure 5 shows the main interface for the last iteration. Throughout the design process, we proposed several approaches for fine-tuning the mapping, i.e., matching the inputs on the peripherals with the commands sent to the drone (MOTOR, PERCEPTION). The maximum speed of vertical, horizontal and rotational movement of the drone can be adjusted using sliders and number boxes (all iterations). The sensitivity of the input devices can be set individually for each joystick axis (iteration 1), calibrated interactively (iteration 2) or adjusted with range sliders (iteration 3 and 4). For interactive calibration, the pilots must first take a comfortable resting position to calibrate the origin of each axis. Then they are asked to move to the extremes on each axis to assign the maximum values. This allows to define the scale change on each axis depending on each users' motor movement. The range sliders, shown in Figure 5.e, are used with pressure-sensitive keys to set the minimum and maximum pressure thresholds for each key. To adjust the calibration, CandyFly provides direct visual feedback of

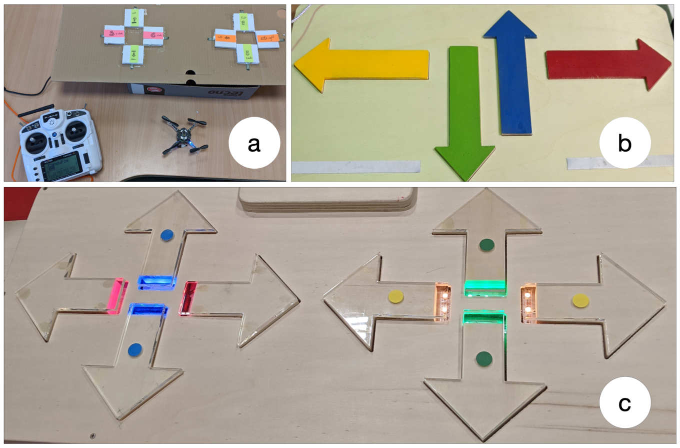

Figure 4: Several iterations of the pressure sensitive arrow controller. Cardboard (a) and wooden table with colored arrow keys (b) and integrated LEDs (c).

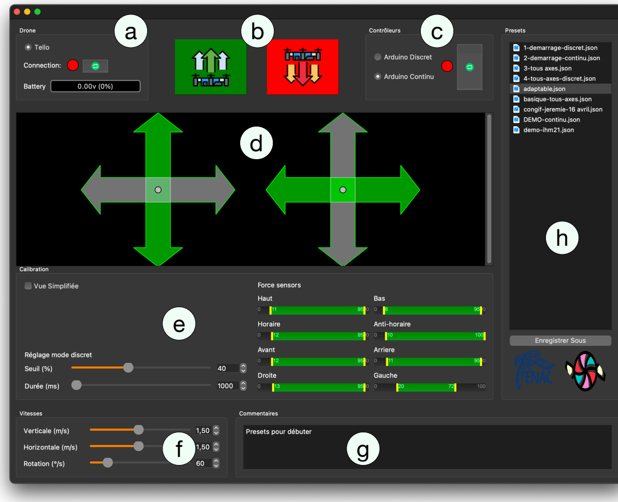

Figure 5: CandyFly GUI. a) drone status, b) button for automatic take off and landing, c) input device status, d) arrows allowing to define active (green) and inactive (gray) degrees of freedom for the drone, e) input calibration to adjust range and delay for button press interaction, f) drone speed controls, g) zone for storing textual notes, h) presets panel.

the command to foster transparency, i.e. "give users awareness of adaptations" [62]. Existing tools such as Logitech G-Hub [39] or the Input adapter Toolkit [12] offer support to remap inputs to required outputs and make existing devices more versatile. However, the former did not cover our available gear and the later did not support piloting tasks.

In terms of automation of the drone piloting, we offer several control modes with different levels of assistance that constitute a continuum from fully automatic control to fully manual control, allowing a progression in the difficulty of the control tasks (STABILIZATION, COMPLEXITY). In the first iteration pilots could choose one of several predefined modes including a mode where yaw is disabled or a fully automatic mode that allows pilots to observe a possible movement of the drone in space without the need to pilot themselves. There is also a predefined mode where the drone follows a determined flight plan regardless of the command used by the pilots. This means that the drone advances on the flight plan when the user presses any key. When the command is released, the drone stops. For the following iterations, we decided to move from distinct predefined modes to a more flexible model. We provided the possibility of activating or deactivating one or several piloting axes (such as the front/back axis, or the up/down axis for example). Pilots or caretakers select the axes directly by clicking on the arrows in the GUI as illustrated in Figure 5). Finally, to facilitate the most critical phases of flight, we have implemented the possibility of automatically taking off and landing with a button on the GUI (COMPLEXITY).

To summarize, the first iteration allowed us to provide the pilots and their caregivers with the basic functionalities of CandyFly such as predefined modes. For the second iteration, we highlighted the main features and introduced the use of axes (diamond shapes) that can be enabled and disabled to replace modes. The third iteration was designed to improve access to important features and limit distraction with a dark graphic style (CONCENTRATION). Axes were represented as arrows. The fourth iteration made all parameters visible on a single interface, integrated range sliders for all keys and has been tested with all supported drones.

5.2 Types of usable drones and safety pilot

Throughout our project, we have made CandyFly usable with different (commercial) drone projects. The first two iterations make use of Paparazzi UAV [33]. CandyFly communicates with Paparazzi by exchanging messages over an Ivy bus [11]. This allows to use an autopilot in the drone (STABILIZATION), to know the position of the drone in space, the charge of its battery but also to send flight instructions. For these two iterations, we used Parrot's Bebop2 either in a flight arena equipped with an external Optitrack positioning system (iteration 1) or outdoors with the GPS sensor (iteration 2). For the third iteration, we chose to use small CrazyFlie drones from BitCraze that are able to fly indoors even without safety nets. We used a Python library provided by BitCraze which includes stabilization algorithms to control the drone. We also used the drone's built-in proximity sensors to reduce the speed as the drone approaches an obstacle to avoid collisions (SAFETY). Finally, for the last iteration we used a tello drone from DJI as it is more stable and provides a greater autonomy than the CrazyFlie. We used the parrot messages API as SDK to send instructions to the drone. We chose affordable commercial drones to respect the commodity principle from ability-based design [62].

For the first two iterations, a safety pilot had to be present to ensure the drone's recovery in case of risk (SAFETY). The safety pilot also turned the drone motors on and off. For the third and fourth iteration, the safety pilot became optional because the risks are lower with the reduced size of the drones.

5.3 Interactions to facilitate the workshops

We added additional elements and interactions within CandyFly to further facilitate the drone piloting workshops. As autonomy of the drone battery is a major limitation for the operation of drones today, the GUI displays the battery status with color levels indicating when it needs to be changed (Figure 5).

As mentioned in the initial observation (section 4), therapists noted on a paper sheet which configurations worked for each participant in order to memorize them for the next workshops. In order to keep track of relevant details more easily (e.g. "P1 prefers piloting with big joysticks"), it is possible to take notes in a text field in the application (Figure 5). From the third iteration onward, the settings made in the application and the notes could be saved, shared and reused in subsequent sessions.

6 PILOTING WORKSHOPS RESULTS

Eight piloting workshops conducted over three years and a half allowed us to observe the pilots using the different iterations of CandyFly (Figure 2). The pilots and their companions (parents or partners) as well as therapists and organizers provided helpful feedback to improve the application and adapt it to their abilities, and suggested new directions to explore. In this section, we describe the results of the piloting workshops grouped by themes, their implications on the design of subsequent iterations, and future perspectives suggested by the participants (pilots, organizers and therapists).

6.1 Having fun piloting with CandyFly

Participants were able to fly the drones most of the time except during workshops 3 and 4. Fewer crashes occurred than in the observation session, independently of the environment (flight arena, outdoors or indoors). This presents a major improvement over the initial observation and was gratifying for the pilots, therapists and organizers. In workshop 3, CandyFly could not be used due to a drone reset removing our auto-pilot. Consequently, the organizers had to reuse their previous drones without stabilization and many crashes occurred. For workshop 4, the table with capacitive keys turned out to be too sensitive for the participants to fly. However, by using radio-controllers instead, some of the pilots were able to have fun flying the drones outdoors as in the second workshop.

The pilots, companions, therapists and organizers were enthusiastic about the possibilities offered by CandyFly despite some technical difficulties during the first four workshops. O1 and O2 insisted that the "reliability of the software and the drone is extremely important, otherwise [the pilots] will lose focus". This led us to use tiny yet very stable drones in iteration 4 and focus on improving the integration of the pressure sensitive arrows within the application.

All pilots expressed their pleasure on multiple occasions and wanted to come back to fly again and try out the modifications they suggested in future sessions. The mother of P1 who accompanied her to the workshops told to us that her daughter was "proud" and that "they both enjoyed" the workshops. Although P1 is non-verbal her mother was able to recognize this because P1 wanted everybody to watch her and touched T1 and T2 hands to confirm that they watched. P3 who participated in several workshops always wanted to increase the drone speed and to take on new challenges such as landing the drone on a tiny card-box. He also invited his girlfriend (P6) to workshop 5 so that she could enjoy flying tiny drones herself. During Workshop 8, Organizers O1 and O3 reported that P7, P10 and P11 had fun piloting with the table with pressure sensitive arrows. O2 stated that P10 "wouldn't stop! I had to change the batteries three times in a row", which corresponds to almost 30 minutes of flight and showed P10's enthusiasm for this activity.

6.2 Adapting to idiosyncratic abilities

During the workshops, participants were able to try several types of controllers and degrees of freedom based on their wishes, abilities, and our suggestions. The pilots needed different adaptations to fly depending on their specific disabilities and individual preferences.

Motor and postural adaptions: The adaptable table designed and built by the organizers was particularly appreciated and was used by all participants, even those with large wheelchairs (see Figure 8.b for instance). T1 and T2 explained that they had to make tiny "adjustments to posture and control device layouts". Participants expressed satisfaction and did not experience discomfort during the activity. For the pressure-sensitive keys (used since workshop 5) we had added markers for the initial positions of the hands (see Figure 8). O1, T1 and T2 explained that it "allowed participants (P1, P4, P6) to clearly understand the expected resting position". This was not the case when using the prototypes that relied on tactile keys or balls of modeling clay connected to the makey makey [17] (Figures 6 and 7). However, with the second version of the table with more degrees of freedom used in workshops 8, pilots P10 and P11 were able to use it without the hand guides. O1 and O3 reported that P10 and P11 found the "pressure sensitive device easier to use and less tiring than the remote controller they used to carry".

Input devices adaptations: Participants, organizers and therapists appreciated the ability to quickly change the input device or the settings to fine-tune the controls to motor abilities. We detail below a few examples that illustrate the adaptations made over time to accommodate requirements from pilots and therapists.

P3 who is a gamer used a video game controller (workshop 1) and did not need the support tablet which was originally proposed to him (Figure 6.b). He really appreciated it and stated that "it is a controller I am familiar with". However, his therapists T1 and T2, did not like the posture he used so they asked us to use another devices with larger motions of the arms. During workshop 2, he used the radio controller with enlarged joysticks (Figure 7.c). In workshop 5 he tried the table with pressure-sensitive keys but explained that "It is too simple for me", even with continuous control. Given his piloting skills, he preferred to train with drones without automation. This is consistent with prior work that identified that participant's previously acquired competences impact their needs and requirements for technology use [6].

P4 used the remote control with adapted joysticks in workshops 1 and 2. Using the two joysticks independently was problematic for him, as he often used both hands in parallel. We therefore deactivated some degrees of freedom like yaw and elevation. We then calibrated the motion gain manually (workshop 1) and then interactively (workshop 2) to define his resting position and the

Figure 6: Workshop 1 performed in a flight arena with the first iteration of CandyFly (drones circled in white). a) P1 (cognitive and motor impairments) uses directional arrows with tactile zones via makey makey [17]; b) P3 (mild motor impairments) pilots with the video game controller; c) P4 (motor impairments) uses the radio control with extended 3D printed sticks.

maximum values he could reach on each axis. This allowed us to adapt CandyFly to his small but precise movements. With this setup, P4 achieved a better level of control and was even able to fly the drone in 3D mode (no yaw) in workshops 1 and 2. Because he was able to relate his actions to their outcomes, T1 and T2 asked us to "limit the use of automation" so that he could improve his motor skills.

The touch table as a unified, yet adaptable controller. Throughout the project, we worked with the organizers to improve the design of the pressure sensitive keys as they believed it was a "promising solution for allowing pilots with various disabilities to fly".

P1 tested the control of the drone with the makey makey interface [17] with aluminum keys and then modeling clay (Figures 6 and 7). We hid the makey makey and the wires to simplify the interface as much as possible. In workshop 1, P1 was able to fly the drone longer than during the Observation, and was pleased with this success. However, it was difficult for P1 to look at the drone while manipulating the controller at the same time. Therapists suggested that the makey makey interface lacked tactile feedback that would allow for non-visual control. The use of play dough improved piloting in the second workshop as it provided some proprioceptive feedback, but P1 still had difficulty removing her hand after pressing the dough buttons. The use of the table with pressure-sensitive keys was designed to solve this problem also encountered with other participants. In workshop 7, P1 did "high fives" with us and her companions to express her excitement. Her mother stated that "is it great to see that it evolved so far from the first version we tried [in workshop 1, Figure 6.a]".

P6 was able to pilot with the first version of the table as shown in Figure 8.a during workshop 5. She needed two or three attempts to determine the amount of force needed to initiate a drone movement using the discrete mode and then was able to fly for several minutes trying increasingly elongated drone movements. P7, P8, P9, P10 and P11 used the second version to fly the drone. P7 used the discrete mode to avoid long motions and enjoyed watching the drone fly in front of her. P8 had fun using the arrows but could not understand the effect of rotation arrows and was confused by the change of orientation of the drone. Despite being low vision, the shape of the arrows helped P9 assess the direction before triggering the command. We added stickers on top of each arrow to support him locate the center of the arrow and thus pressing it at an optimal location (the touch contact was best at the center of the arrows). P9 explained that "the control using pressure-sensitive keys of the table was nice and practical, but that it would not be useful for all visually impaired people as it would depend on the degree of visual acuity". Since P9 has a background in aviation, he preferred to pilot with a real remote controller and also enjoyed flying regular drones without adaptations during the workshop. P10 and P11 appreciated that it was "simple to fly at the beginning, yet challenging with many possible motions" as reported by O3 who started with only vertical motions before adding additional degrees of freedom. P11 explained to O1 that he enjoyed flying with the table more than with the remote controller as it was simpler to perform specific motions such as surrounding an obstacle.

O3, who built the table, was very positive about its use with CandyFly and the piloting possibilities. However, the discrete mode was not adapted to all pilots. He explained that "for some pilots it would be more valuable to send the command when the key is released because they cannot look at the drone while pressing". He also wished that we could integrate "a delay between press on the arrows for a pilot who has tremors".

6.3 Sense of control

Pilots mentioned a need for controlling the drone's movements to be able to appreciate the activity. For example, the automatic mode was not well received by participants P1, P3 and P4 who wanted to pilot the drone at least on two axes, and especially in altitude. P3 asked us to "enable altitude control" so that he could "fly as before" without our system.

For participants with cognitive impairments, therapists T1 and T2 explained that the cause and effect relationship between the commands and the drone's reaction had to be fast and very strong on several levels. O2 who is a skilled drone pilot himself also insisted on the importance of the "fast causal link between commands and drone motions". The time between the execution of a command and its effect had to be minimized. For example, in the second workshop, we used a positional control of the drone, i.e. the command incremented the position of the target to be reached by the drone. Since the drone was captive (i.e. attached to a support), there were situations for P3 and P4 where the set point was relatively far

Figure 7: Workshop 2 outdoors with the second iteration of CandyFly (drones circled in white). a) P1 (cognitive and motor impairments) uses directional arrows with balls made of modeling clay and makey makey [17]; b) P4 (motor impairments) pilots with the radio control with adjusted resting positions and gains; c) P3 (mild motor impairments) uses the radio control with sticks (the joystick on the right is used by the safety pilot).

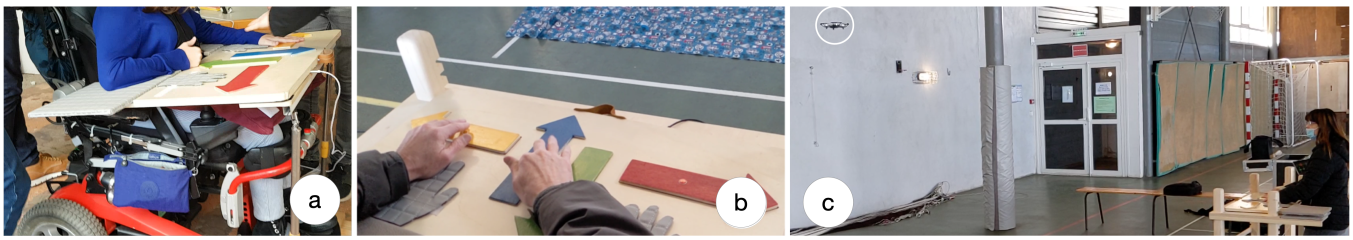

Figure 8: Workshop 5 and 7 indoors with the third and fourth prototype. a) adjustment of the table to the chair of P6; b-c) P9 and P10 piloting the drone using arrows with pressure control. Grey hand markers indicate the initial resting position.

away because they overshot the flight area and they had to hold the joystick in the opposite direction for a few seconds before the drone changed direction. This was a source of frustration and they both wanted us to change this behavior. This phenomenon was avoided by using a speed control from iteration 3 on which reacts quickly to the requested command. O2 stated that speed control was the "closest automated control to fully manual control" on the automation-manual control continuum.

The use of the table with the capacitive keys led to some unintended touch detection when the hand passed near the sensor which resulted in unwanted drone movement. This cause and effect relationship was not understood and the pilots P1 and P4 told us that they did not want to use this interface if the behavior was unpredictable. Pressure sensors allowed us to overcome this limitation. The visual and audio feedback when using the table was appreciated by pilots (P7, P8, P10 and P11) during workshop 8. As reported by O1 and O2, it "helped them feel in control of the drone" and "be sure that the motions of the drone were caused by their actions". They also explained that "the sound helped P8 to focus on piloting, but it has made it difficult for P7 to concentrate who asked the organizers to turn off the sounds".

When we presented our interactions to control the drone by shaking an object or spinning it, T1 explained that "this would not be suitable for participants with cognitive impairments". T1 and T2 explained that "the direction of the gesture in space had to correspond to the direction of the drone to maintain a causal link between action and reaction". We consequently decided not to test these interactions with our participants.

6.4 Workshop safety

The safety of the participants was a strong constraint for the organizers. O1 and O2 insisted on the fact that "the participants must be safe during the workshops". To ensure safety we conducted the workshop inside a flight arena (workshop 1) or made use of captive drones, i.e. attached to a support, when flying outdoors (workshop 2). A few minor incidents occurred to the material, such as several broken propellers and a damaged motor. When using the small BitCraze drones the behavior of the drones was sometimes inconsistent due to bent propellers or poor battery attachment. O2 and O3 suggested to modify the drone itself with 3D-printed elements or to ask other members of the fablab to look into the stabilization algorithm. Using an anti-collision algorithm that limits speed when an obstacle is close to the drone prevented several shocks to the ceiling, but could not prevent some side shocks to furniture. O1 found it "reassuring" but O2, O3 and pilots found it disturbing that the drone stops moving and does not react as commanded. The Tello drone was assessed as "light and stable" enough to be used at a few meters from the pilots without major risks by O1, T1 and T2. To ensure the pilots were able to handle the level of difficulty and minimize the risks, O3 explained that he "first assesses pilots abilities without front-back and rotation before adding more degrees of freedom."

6.5 Note taking and reuse of settings

As explained above, CandyFly allowed Organizers to use presets for each participant and to take notes to facilitate the workshops. The organizers made three basic presets (simplified discrete, simplified continuous and three directions continuous) from which they started adjusting parameters for each pilot. These presets were notably used in workshop 5 to adapt the setting of pilots P3 to P6. O3 also saved presets corresponding to P7 and P8 from workshop 6 as he 'knew they would participate in a following workshop". O3 also reported that during workshop 8 he "made and used two default presets as starting points that [he] then updated and saved for P10 and P11". We did not observe any real use of the text field except for the description of the settings. O1 explained that "it is too difficult to take notes while making sure everything works".

7 ADAPTATION FRAMEWORK

While designing CandyFly and using it in workshops with pilots with disabilities, we identified and refined design principles spanning three areas of adaptation: hardware, software and automation. These three axes constitute a framework that helped us meet the needs of the users and guided us during the design phases. We present these axes based on CandyFly, link them to the requirements and generalize them to make them useful for designers of similar systems. This framework provides guidelines for implementing the adaptation principle of ability-centered design [62] for leisure activities involving control of drones or robots.

7.1 Material adaptations

Given the variety of disabilities and individual preferences, our results highlighted the need for flexibility in terms of physical controllers in order to adapt to the diverse motor abilities of the users (MOTOR). Indeed, existing remote controls [36] can be complex and distract pilots (CONCENTRATION) or not be adapted to their postures and their possibilities of movement (MOTOR). While previous research demonstrated that ad-hoc interactions and devices can be used to fly drones [58], reusing commodity drones and input devices as suggested by ability-based design principles [62] was satisfying for many of our pilots. In our work we found that both approaches can work depending on the abilities of the pilots. The table with pressure sensitive arrows facilitated access to the activity for participants with stronger disabilities and beginners, while pilots with more experience and abilities preferred using conventional hardware with less adaptations. We thus suggest to use a variety of controllers, including existing game controllers, remotes, software keyboards, but also innovative interfaces that can be easily reconfigured, for example by changing the position or shape of the controls. Microsoft Xbox adaptive game controllers [44] are good examples of this type of specialized hardware. Physical support can be provided by using foam supports placed under the forearms of participants or adjustable tablets (MOTOR). Using longer joysticks than on commercial radio controls also improved pilot performance and satisfaction (MOTOR).

Providing pilots with consistent cues between the drone, the remotes, and the space should be considered (CAUSALITY). Color associations between the physical controller and the space may help understand directions. The system needs to be reactive so that the link of cause and effect is understood. Using sounds to confirm interaction can help to focus and feel in control. However, it may also disrupt concentration for some people (CONCENTRATION). While multimodal feedback has been found to be valuable for older adults with cognitive impairments using their wheel chairs [60], we argue that it should, in our leisure context, be enabled or disabled according to pilots' preferences.

To limit the risks, we used a flight arena and tethered drones (SAFETY) but this sometimes made P1 and P4 lose their focus (CONCENTRATION). Using drones with protections around the propellers or constraining the flight area through the drone's auto-pilot are avenues to explore (SAFETY).

7.2 Software adaptations

Because each participant has very different ranges of motion and accuracy for his hands, tools must be provided to calibrate and adjust the interactions to the drivers' strength and accuracy. For some, the rest position is not necessarily the center position of the joystick because it depends on the physical supports which are used. We suggest to allow an adaptation at the software level (MOTOR), which is consistent with Wobbrock et al.'s recommendation that "applications must offer a much wider range of possibilities to fully support ability-based design." [62]. For example, software can set the zero position of a joystick to a user's resting position or increase the gain to allow very precise movements with small amplitudes. Other possible adaptations include using a filtering function to minimize unwanted input such as from tremors.

To make it easier to perceive the drone and its movement, we suggest limiting some degrees of freedom such as depth displacement or yaw (PERCEPTION, COMPLEXITY). It could be desirable to limit the flight domain of the drone so that it remains always in the field of vision of the pilots. This could be done using eye-tracking or a priori knowledge of their field of vision. The choice of low speeds at the beginning allowed pilots (P1, P4 and P6 for instance) not to lose sight of the drone during rapid movements or when the drone changes orientation (PERCEPTION, CONCENTRATION). The gradual increase in the drone's speed as well as adding new degrees of freedom can be a source of fun for pilots (FUN) and an indication of their progresses.

7.3 Adaptation through automation

Stabilizing a drone in the air is a particularly complex task for the pilot because it requires continuous adjustment of the thrust of the motors and the inclination of the drone. Moreover, some flight phases are particularly difficult such as takeoff and landing. Those complex tasks can be mastered easier by automating them (STABILIZATION, COMPLEXITY). Automation may allow the pilots to fly drones much longer and without incidents, which can be a source of pride (FUN). Pilots generally prefer controlling the flight direction themselves, than advancing on a predefined flight plan, although the latter may be easier for beginners and people with some types of impairments (CONTROL). The use of automation which can progressively be disabled (such as degrees of freedom of movements) are more appropriate to respect the playful aspect of the activity (FUN).

8 DISCUSSION

By using our adaptation framework while designing CandyFly, we succeeded in increasing the pleasure of flying by providing adapted and adaptable interactions. Personalized settings are accessible and adjustable by the users and their companions which allows a great flexibility to support multiple disabilities as this has been suggested in the context of ability-based design [62]. Yet, it remains difficult for caregivers to decide on a desirable initial configuration for a new participant. Using automated approaches that determine input parameters based on user modeling such as SUPPLE [26] could facilitate adaptation of CandyFly. The therapists in our project designed a questionnaire to characterize the pilots' impairments, and it would be particularly interesting to integrate these questions into our application in order to compute relevant speed or automation parameters. Going further and being able to suggest evolution of the parameters over time such as "increase or decrease the challenge" could also further promote pleasure.

We modified CandyFly's interactions throughout the project to maximize their cause and effect relationship as well as the feeling of control for the pilots. We did not explore the potential of direct manipulation such as proposed by Gomes et al. [28] since the organizers and therapists wanted the activity to be real piloting. The third and fourth iteration with the pressure-sensitive table and arrows provided great satisfaction to the pilots at workshop 5 and the therapists indicated that they wanted to continue with this version. Indeed our device is simple, and as shown by prior work [19] simplicity in use, configuration and replacement is important for the adoption of technology by people with cognitive impairments. Several perspectives are envisioned with the organizers to make piloting with the table suitable for people with various abilities. For instance, some participants were not able to quickly press or release the pressure sensitive keys which resulted in continuous motions in one direction or no motion at all. We will explore different interactions to cover these needs in future iterations. Moreover, we were not able to explore CandyFly for all types of disabilities (e.g., only one participant was low vision or blind despite drone piloting being of interest to people with visual impairments [25]) and hence more workshops with users with different abilities are planned for the future.

Throughout the project, we used a research-through-design [63] process involving users with various disabilities and their therapists. As demonstrated by previous work [7, 31], it was important to involve the family and caregivers to make pilots' needs, abilities and desires explicit. This was especially important since some of our participants were unable to communicate verbally. Working with such a multidisciplinary team required to use adequate design techniques. Observing and formalizing requirements helped us validate important challenges and ensure to cover the organizers' and therapists' goals [40]. By providing usable technology, we engaged not only with organizers and therapists but directly with pilots which might not have been possible via low fidelity prototypes [34]. Yet, documenting such a long process with people with disabilities has proven difficult. For instance, for the workshops that took place without our presence using Candyfly as a technology probe (workshops 3, 4, 6 and 8 in Figure 2), we were not always able to collect detailed information on the participants. In addition to the participants described above, the organizers mentioned at least four children between 7 and 10 years and three young adults who took part in the workshops. However, we do not have any information about their experience of using our technology.

During our design activities we applied principles of ability-based design [62] and reflected on its use in a practical context. We were notably able to apply 5 out of the 7 principles proposed by Wobbrock et al.: ability, accountability, adaptation, transparency, and commodity. It would be interesting to further investigate how the remaining two principles context and performance could be included in CandyFly in the future.

According to the therapists and the workshop organizers, CandyFly could be used by other pilots and associations. In fact even people without disabilities that attended the workshop as companions or family enjoyed using CandyFly, often with settings to maximum speed and all degrees of freedom. We hope that our system can support people with and without disabilities to practice a leisure activity together which can promote social and communications skills [22]. We also believe that this could be interesting for children who start learning to fly drones, as well as for elderly people as a fun activity that helps to maintain cognitive skills.

We released the source code and the documentation online to make it accessible to others as an open-source project [27]. The members of the drone section of the Artilect fablab created an association to share and promote the table with pressure sensitive arrows. We hope that this will enable more people to benefit of accessible drone piloting activities.

9 CONCLUSION

In this paper, we present our work to support people with disabilities to have fun while flying drones. Following a research-through-design approach [63], we conducted an iterative design process with an association for people with impairments and a fablab over three and a half years with a total of eleven pilots with various disabilities. Initial observations allowed us to identify eight requirements: FUN, CONCENTRATION, SAFETY, PERCEPTION, MOTOR, STABILIZATION, CAUSALITY and COMPLEXITY. We introduced CandyFly, an adapted and adaptable application that allows pilots with various cognitive, motor and perceptual impairments to fly drones as a leisure activity and is based on principles from ability-based design [62]. Pilots tested CandyFly with different controllers and types of drones in a series of workshops. Our results indicate that our adaptation framework combining hardware, software and automation adaptations allowed the pilots to have fun and progress through the workshops. The pilots, their therapists and families expressed their pleasure on multiple occasions as well as their willingness to continue the piloting workshops. We hope that our requirements and framework axes can be used by designers of other assistive technologies and leisure systems.

Future work will include pursuing workshops to make CandyFly adapted to other impairments such as visual impairments. We also want to continue the work on new interactions to facilitate personalizing settings for different types of impairments and abilities, and possibly suggest several levels of difficulties or challenges.

Finally, we believe that this work could be beneficial to other user groups, such as young children who learn to fly drones, elderly people for maintaining cognitive activities, or professional pilots who have to work in degraded conditions.

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