Last-Centimeter Personal Drone Delivery: Field Deployment and User Interaction

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***Abstract*—Drones are rapidly becoming an affordable and often faster solution for parcel delivery than terrestrial vehicles. Existing transportation drones and software infrastructures are mostly designed by logistics companies for trained users and dedicated infrastructure, and are to be used for either long range (<150 km) or last-mile delivery (<20 km). This letter presents *Dronistics*, an integrated software and hardware system for last-centimeter (<5 km) person-to-person delivery using cargo drones. The system is conceived to be intuitive and intrinsically safe to enable short-distance deliveries between inexperienced users. Dronistics is composed of a safe foldable drone (PackDrone) and a web application software to intuitively control and track the drone in real time. In order to assess Dronistics' user acceptance, we conducted 150 deliveries over one month on the EPFL campus in Switzerland. Here we describe the results of these tests by analyzing flight statistics, environmental conditions, and user reactions. Moreover, we also describe technical problems that occurred during flight tests and solutions that could prevent them.**

***Index Terms*—Aerial systems, applications, intelligent transportation systems, unmanned aerial vehicles.**

I. Introduction

RECENT years have witnessed an exponential rise in interest in delivery drones, and mainly multicopters, due to their capability to effectively overcome obstacles or traffic jams, to rapidly reach remote locations, and to take off and land in cluttered environments. Therefore, logistics companies have started to explore the possibility of using aerial delivery as a faster and more cost-effective alternative to terrestrial transportation [1], [2]. Examples include Amazon.com's tests of product deliveries to homes directly from warehouses in the United Kingdom [3], DHL's deliveries of emergency medical supplies using its Parcelcopter [4], Alphabet's burrito deliveries to Australian homes with its Project Wing drones [5], Swiss Post's experiments with transportation of lab samples between hospitals in Lugano, Switzerland [6], and Zipline's transportation of blood from central storehouses to remote hospitals in Africa [7].

All these aerial delivery services are developed for operation by trained employees of logistics companies for business-to-business (B2B) or business-to-client (B2C) operations. Consequently, the software framework used to control and navigate delivery drones is proprietary and is not designed for inexperienced users. In addition, most of the drones are designed for long-distance delivery (around 150 km) or last mile delivery (around 20 km) [8]. Covering long distances requires bulky platforms that do not allow for personal delivery due to storage and transportation difficulties. Furthermore, take-off and landing spots should be specially prepared and must be located at safe distances from users to prevent contact with dangerous unshielded propellers. Thus, these drones do not deliver directly to people's hands in the way that mail carriers or courier services often do.

In this letter, we present an integrated hardware and software solution for last-centimetre, short-range delivery through which people can exchange goods safely through the air. Items arrive directly to their recipients' hands without the need of intermediate logistics companies, dedicated infrastructure, or trained operators. This approach could be suitable for person-to-person exchanges within private grounds, such as large governmental or industrial campuses, construction sites, hospitals, or harbours. Additionally, last-centimetre delivery could be suitable for dispatching parcels vertically, to the top of cranes and scaffoldings, or to the bottom of deep opencast mines.

The proposed Dronistics system consists of a safe quadcopter called the PackDrone [9] and a customisable software framework. The PackDrone has a foldable structure that shields the propellers to ensure people's safety. Additionally, folding the origami inspired structure significantly reduces its volume, allowing for its easy storage and transportation in small containers. In parallel, the web-based software allows recipients and senders to intuitively control parcel exchanges and monitor flight trajectories in real-time while ensuring flight safety.

The literature contains several studies of the societal impact of drones [10], drone use in the context of governance, ethics, and privacy [11], growth of the drone market [12], possibilities of using drones in urban environments [13], drone efficiency [2], the economic benefits for last-cm delivery with trucks [10], and the dangers of falling drones [15]. However, no field studies have yet investigated practicalaspects of drone delivery such as the behaviour of inexperienced users when operating delivery drones, the reliability of the hardware and software, and the impact of weather conditions on day-to-day operations.

The goal of this letter is to present the results of the deployment of Dronistics on the campus of the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, focusing on the aforementioned issues of inexperienced user behaviour, hardware and software reliability, and the effect of the changing weather conditions on daily operations. We conducted 150

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Fig. 1. Three phases of delivery on the EPFL campus. (a) The PackDrone just before take-off at the sender location. The sender is operating the software from a tablet. (b) The drone is flying above the EPFL campus. (c) The drone in a recipient location. The recipient is unloading a parcel.

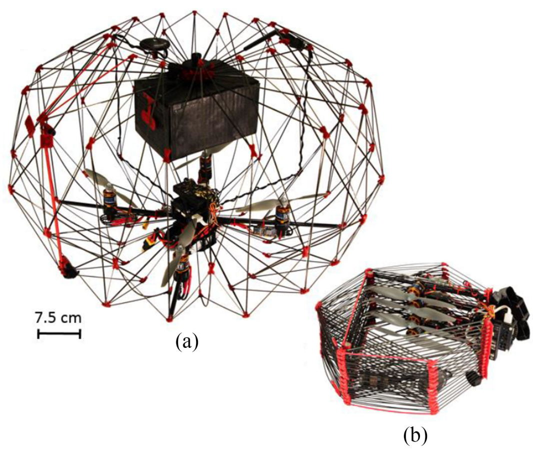

Fig. 2. The foldable PackDrone for last-cm delivery. (a) Deployed configuration with an enclosed carton box containing the parcel. (b) Folded configuration with a volume reduction of 92%.

delivery flights between July and August of 2017 (Fig. 1). This real-life field study was largely successful, but also highlighted critical issues in last cm-delivery that must be addressed in future developments.

II. The Foldable PackDrone

The PackDrone (Fig. 2) is a quadcopter designed for safe cargo delivery [9]. Its arms and propellers are an integral part of a foldable protective cage that wraps around the parcel, which is placed in a box attached to the top part of the cage. The box can be opened on the side to remove the parcel (Fig. 5(f)) or can be entirely removed from the drone. The cage also acts as barrier between the propellers and the environment, protecting the drone and its cargo in the event of a collision and shielding bystanders from dangerous spinning propeller blades. Moreover, the cage lets people grab the PackDrone safely in the air as it approaches its recipient. This allows deliveries in situations without landing spots, as is often the case for workers on scaffoldings, and people stuck in traffic jams or in emergency situations. The cage can be opened sideways to place or retrieve a parcel; to further ensure safety of inexperienced users, integrated switches automatically turn off the propulsion system while the cage is open. Another unique feature of the PackDrone is its foldable design. The drone can be folded with a single hand movement to reduce its volume by 92% (Fig. 2(b)), thus allowing storage in a backpack or in an office drawer.

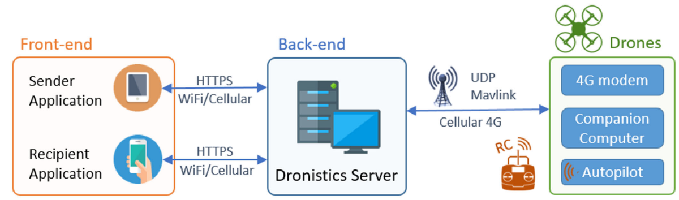

Fig. 3. The architecture of the Dronistics software framework.

III. The Dronistics Software

The Dronistics software framework has three key features to ensure inexperienced users can use delivery drones intuitively. First, it makes the delivery process fully automatic, minimising the number of operations that users must perform. Second, it is compatible with multiple operating systems and drones in order to facilitate portability and adoption. Third, it ensures safe communication and privacy of user's personal data. To achieve these key features, the Dronistics software framework is based on a web application [16] and has an overall architecture composed of three main parts: a front-end layer composed of the Sender and Recipient Applications; a back-end layer composed of the Dronistics Server, and a Drone layer composed of the drone software (Fig. 3).

The front-end software is hosted on a mobile device, such as a smartphone, tablet, or laptop. It has a simple graphic user interface for sending and receiving parcels with a small number of user commands. This interface also displays the position of the drone in real time. The software is compatible with different operating systems such as macOS, Android, Microsoft Windows, and Linux. The back-end software is hosted on a secure server and is responsible for automating the whole delivery process. It computes the drone's path, performs safety checks, and handles real-time communication between the user and the drone. Moreover, all the personal data of the users are stored and processed on this secured server. The drone software is hosted on a companion computer on-board the drone and creates a bridge between the drone's autopilot and the Dronistics server through an internet connection. The companion computer is independent of the specific autopilot software and hardware, ensuring the broadest compatibility. Finally, a connection to the internet via the omnipresent GSM network enables control and real-time tracking of the drone over the whole flight path. The system is easily scalable to multiple drones flying simultaneously given sufficient access to servers and communication bandwidth. The three software layers and their features are described in detail in the following sections.

A. Front-End Layer: Sender and Recipient applications

The sender and recipient applications are developed using front-end tools (HTML, CSS, and JavaScript) with a responsive user interface in order to create an accessible and intuitive software with secure communication. This allows the applications to run in any browser on any portable device independently of its operating system. Users can access the corresponding application by navigating through the respective URLs on the Dronistics Website. All communication between the front-end and the back-end is established with Asynchronous JavaScript, XML (AJAX) and is encrypted with SSL certification for enhanced security.

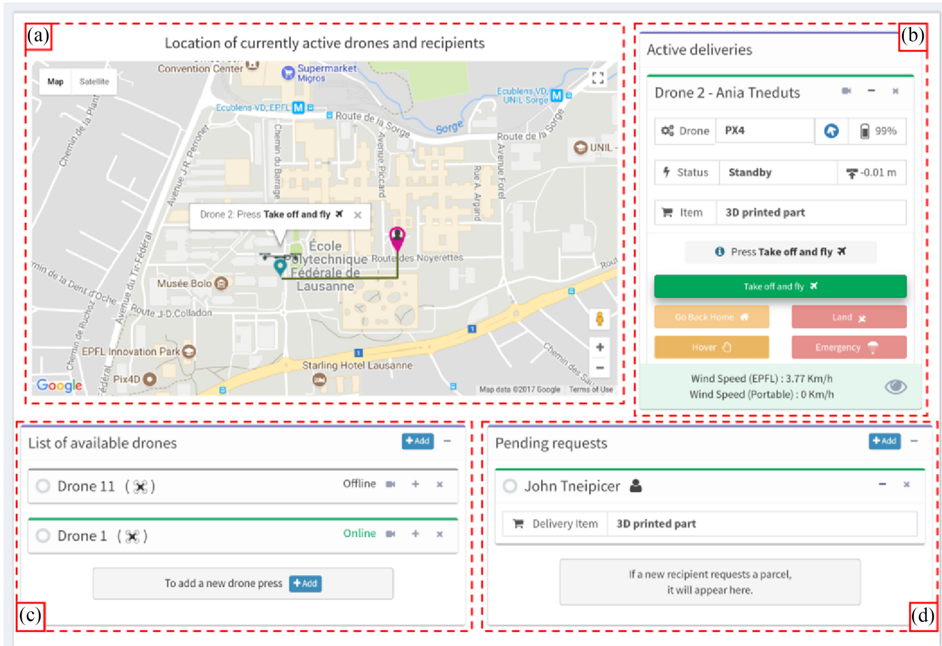

Fig. 4. The interface of the sender web application composed of four panels marked from a to d. (a) A map with the real-time position of drone(s), the location of users and the path of active deliveries. (b) The list of active deliveries. (c) The list of drones that are owned by this specific sender. (d) The list of pending requests. The location of the specific recipient is presented on the map as a pink user icon.

The Sender Application is a web-application that displays all the information and functions in a single window. It is currently designed to allow parallel dispatching of multiple drones to multiple users. To access this application, the user has to register and/or login to the Dronistics system as a sender. The Sender Application is composed of four panels a, b, c, and d (Fig. 4). Panel a is a map (interfaced with Google Maps), that shows the real-time position of the drone(s), the location of the user(s) and the paths of active deliveries. Panel b shows the list of active deliveries, and any drone control command can be issued only from this panel. This panel also shows the wind speed from various nearby weather stations. Panel c contains the list of drones owned by the sender. A sender can add drones into the application by specifying the drone ID. Each drone can be online or offline. Panel d contains the list of pending requests with the name of the user and the requested item.

The entire delivery process requires only three steps. In the first step, the sender has to register and/or login to the system. In the second step, when the sender receives a request for delivery, it assigns a drone to the recipient. Once the assignment is made, the drone and the recipient disappear from their respective locations in tabs C and D, and appear as an active delivery in tab B. For example, in Fig. 4(b), the sender has assigned Drone 2 to recipient Ania Tneduts for the delivery of 3D printed parts. The Active deliveries tab of the Sender Application also shows real-time telemetry data, such as battery status, altitude, and delivery status. To ensure the reliability of deliveries even in the event of a communication disruption, the back-end server computes the entire flight plan and uploads it to the drone before take-off. In the third and final step, the sender loads the requested parcel into the drone and triggers the mission by clicking on the *Take Off and Fly* button. Additionally, the sender can issue commands such as *Go Back Home* (drone returns to the sender's location), *Land* (drone lands at its current location), *Hover* (drone holds its position in the air), and *Emergency* (drone disengages the propulsion system and deploys a parachute, if installed) during the mission.

The Recipient Application guides a user through the delivery process in three simple steps. Its current design allows the request of only one delivery at a time. The first step is to register or login into the recipient web application (Fig. 5(a)). In the second step, the recipient can select from a list of different senders and items to be delivered, and specifies the delivery location using a map. During the field tests reported herein, this second step was further simplified by specifying a fixed delivery location due to security constraints (see Section IV), and instead, the application guided the recipient towards the delivery location (Fig. 5(b)). After this step is completed by the recipient, the sender receives the request and sends the drone with the specified item. The recipient is informed (Fig. 5(c)) and can monitor the drone in real-time during the onward-flight (Fig. 5(d) and (e)). The third step consists of retrieving the parcel and sending the drone back. This step is guided by a short photo tutorial displayed on the screen (Fig. 5(f) and (g)). On pressing the *Send the drone back* button, the web application reminds the recipient to ensure a safe space around the drone for take-off and triggers a countdown before the drone takes-off (Fig. 5(h) and (i)). For the purpose of these delivery tests only, an additional anonymous survey form was displayed after the drone took-off in order to gather feedback from recipients.

B. *Back-End Layer: The Dronistics Server Software*

The back-end layer plans the flight path as follows: no-fly zones, determined using information about surrounding obstacles (e.g., buildings, trees, or mountains), and from live

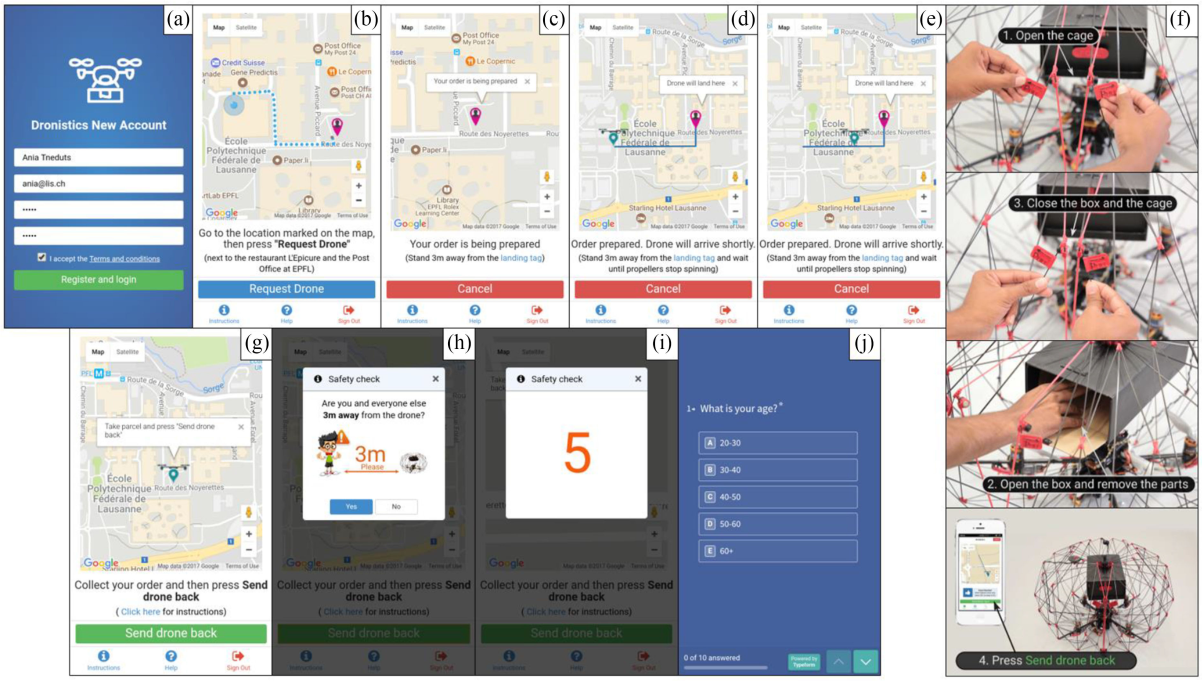

Fig. 5. Recipient web application with the stages of delivery shown on the screen. (a) The registration screen. (b) The dotted path guides a recipient (big blue dot) to reach the landing spot (pink icon). (c) The web app informs that the sender is loading a drone. (d) The web app shows that the drone was matched with the recipient and is ready to fly. The path of flight appeared. (e) The web app shows the real-time position of the drone. (f) After the drone has landed, the web app displays a short photo tutorial explaining how to open the cage and remove a requested item from the drone. (g) The web app shows readiness to send the drone back to the sender. (h) The web app informs about securing the space around the drone for take-off. (i) A countdown is launched to inform recipient when the drone will take-off. (j) When the drone takes off, a survey appears on the screen for the recipient. The web app automatically logs the user out after answering all the questions.

meteorological data gathered by nearby wind stations, are encircled on the map. The shortest path between the sender and the recipient is then calculated, flying tangentially around the edge of any no-fly circle which may lie on the trajectory. The back-end layer also acts as a middleware between the front-end layer and the drone layer. Hence, it not only provides real-time data of the drone to the front-end but also receives operational commands such as *Take-off*, *Land,* and *Hover* from the front-end and forwards them to the drone.

Additionally, the backend layer receives wind speed data from a wind station mounted on top of a building close to the recipient's location and transfers it to the front-end for visualisation. The back-end layer resides on a Java-based Apache Tomcat Server web-server. The relational database (built using PostgreSQL) is an integral part of this layer and allows the storage of all information regarding drones and deliveries. In addition to the web-server that acts as a communication entity of front-end, the back-end layer runs a UDP thread that allows bidirectional communication between the web-server and the drones in real time. As this communication is encapsulated in an independent thread, multiple drones can communicate with the server in parallel, thereby providing scalability of the system for future applications. Additionally, the back-end layer runs on the server with static IP address (with a public Domain Name Record), to enable back-end communication of front-end devices and drones over the internet.

C. The Drone Software

The drone software architecture, which reflects the hardware architectures, is composed of three elements: an autopilot, a companion computer, and the 4G modem (Fig. 3). The companion computer is designed to be compatible with different autopilots that use the common MAVLink protocol for communication [17]. It hosts the Dronistics software and acts as an interface between the autopilot and the Dronistics server.

The autopilot is responsible for controlling the drone and executing the commands from the Dronistics server. Typical examples of these commands include: *Landing, Take off and fly, Emergency*, etc. In addition, the autopilot can communicate directly with the remote control of a safety pilot, who can override the Dronistics software at any time and manually control the drone. This feature is a legal requirement which is useful in emergency situations. The autopilot used for this field test is the PixHawk board with PX4 software framework.

The Companion Computer is an on-board lightweight Linux computer that is responsible for communication between the autopilot and the Dronistics server. This computer can also be used for other features that cannot be handled by the autopilot, such as sensor-based obstacle avoidance or audio and video communication. The companion computer used in this field test is XU4 Odroid board.

The 4G modem is a USB dongle for hybrid (3G and 4G) internet access of the companion computer in order to enable bi-directional communication between the drone and the server.

IV. Field Test

The field test consisted in delivering various objects of up to 250 grams between EPFL campus employees and students. The tests were designed in compliance with three regulations set by the Swiss Federal Office of Civil Aviation (FOCA) [18] and by the EPFL Security Office [19].

Firstly, drones must always be kept within Visual Line of Sight (VLOS) and at least one operator must be able to intervene and land the drone in case of an emergency. Secondly, the PackDrone must be operated at a distance of at least 100 metres from a crowd (defined as a gathering of 24 or more individuals) since its mass exceeds 500 grams when fully loaded. Thirdly, the drone operators must receive authorisation from the nearby Lausanne Airport, since the EPFL campus is within 5 km of the airport grounds. Such authorisations can be revoked at any time by the airport authority in case of emergency situations to prevent interference with manned aircraft traffic. To comply with these rules, we conducted the autonomous drone delivery tests between two fixed points on the EPFL campus under the supervision of three people: a safety pilot and two observers, one at the sender location and the other at the recipient location. The flight path is indicated by the green line in Fig. 4. The first point (denoted by the drone in Fig. 4, tab a) is the sender's location, adjacent to the EPFL campus workshops where 3D printed parts and Printed Circuit Boards (PCB) are fabricated for all campus employees and students. The recipient point was located near a post office at EPFL. The flight path was not the shortest trajectory between sender and user locations but was instead planned to fly over less crowded areas to reduce the risk of accidents. To ensure visual contact with the drone during the entire flight, the pilot stood in the centre of the flight path, which was limited to a total distance of 300 metres. A failsafe function was included to make the drone land immediately in the event of a malfunction of the pilot's remote controller. We also limited the drone's speed to 6 m/s to facilitate a potential manual takeover of its controls. Additionally, we set the flight altitude to 15 metres above the ground (5 metres above the tallest building on the flight path) to allow direct line of sight with the safety pilot on the ground and provide a significant distance between the drone and any manned air traffic from the nearby airport. At the sender location, a person was responsible for loading the cargo and for different safety procedures. He could trigger safety procedures from the Sender application, such as hover, land, return home, or disengage the propulsion system in case of an unexpected behaviour. We recruited trained students to act as senders for safety purposes while conducting experiments to verify landing precision in proximity of buildings, trees, and a road. Thus, they could react quickly if the drone flew too close to obstacles or exhibited undesired behaviour due to GPS signal reflections. Since the procedures for loading and unloading the drone are very similar, the users' behaviour when operating the drone was analysed at the recipient's location.

Drone deliveries were carried out only between 9–11 AM and 2–4 PM to avoid flying over crowds that could gather during breaks. The drone delivery service was announced to the EPFL community and a website was set up (dronistics.epfl.ch/EPFL). Interested users could register by logging their email and delivery time availability. When the requested item was ready, an email specifying the exact delivery time was automatically sent to the recipient. We gave the recipients the possibility to receive 3D printed parts, printed circuit boards, or a surprise package containing sweets. While the average weight of all the delivered items was 150 g during the experiments, the drone can carry up to 500 g of payload. All the items were placed in a box ($14 \times 18 \times 11\,\mathrm{cm}$) and surrounded by air bubble film that prevented the items from shifting during flight.

TABLE I
INSTRUCTIONS PROVIDED IN THE RECIPIENT APPLICATION AND THE PERCENTAGE OF PEOPLE WHO FOLLOWED THE INSTRUCTIONS

Instructions in the recipient application	Percentage
Wait 3 metres away from the landing tag	99%
Monitor the drone's flight in the web application	74%
Follow the photo tutorial to unload the parcel	80%
Open the cage	99%
Open and close the box	98%
Step back more than 3 metres from the drone	99%
Ensure a safe space around the drone before take-off	6%

TABLE II
UNEXPECTED BEHAVIOURS AND PERCENTAGE OF THE PARTICIPANTS WHO REPEATED THE SAME ACTIONS

Unexpected behaviour of the recipients	Percentage
Recipients took photos and videos while the drone was in flight	17.7%
People took photos of the drone and with the drone on the ground	7%
Confusion about the procedure after the drone landed	8.5%
Uncertainty on how to handle the mobile device while operating the drone:	
Holding the device in their hand while operating the cage	32%
Placing the device on the ground	48%
Keeping the device in a pocket while opening the cage	20%

The participants were free to use their own internet-connected device (smartphone, tablet, or laptop). We recorded the behaviour of the recipients on video for further analysis. We informed the recipients of this fact during the registration process, in which each person had to read and consent to the Terms and Conditions (Fig. 5(a)). The recorded videos could only be used for internal data analysis. However, the reader could request any additional data recorded during the tests by emailing the authors. As the Recipient application provides all the necessary information, recipients were not given additional help. Nevertheless, the person recording videos was acting as a second observer who could report dangerous situations to the safety pilot or the first observer (sender) using a walkie-talkie.

V. EXPERIMENTS AND DISCUSSION

In this section, we present and discuss the results of 150 aerial deliveries performed on the EPFL campus.

A. Behaviour of the Recipients

We expected that the recipients would follow the instructions provided in the recipient application. To measure this hypothesis, we filmed 141 recipients who consented to be recorded, and measured the percentage of individuals who followed each instruction (Table I).

During the tests, we also observed various unexpected behaviours, which are grouped into the categories presented in Table II.

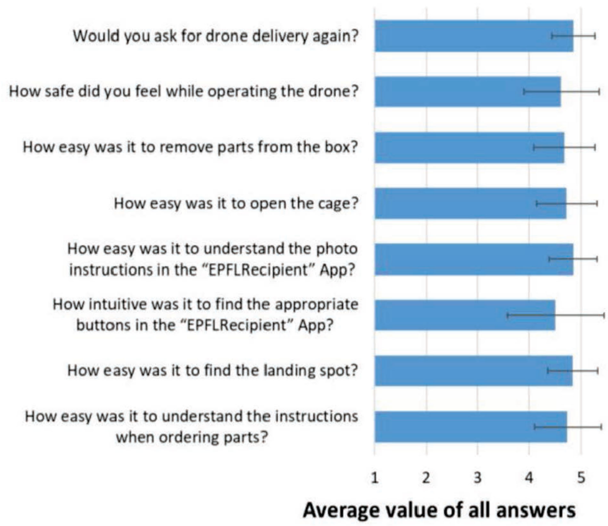

Fig. 6. Survey questions and average numerical answer. Questions could be graded on a five-level scale, where value 1 means *Hard/No* and value 5 means *Easy/Yes.* Whiskers represent standard deviation. Two questions are not presented on the plot: the first question asking for the participants age and the last open question asking for recipients "Additional comments". Answers to both of the questions are presented in the text below.

The analysis of the videos revealed that four out of the seven instructions of the tutorial were followed by more than 98% of the participants. However, only 74% of the participants monitored the flight of the drone in the web application, mostly because they were distracted - taking photographs, recording videos, or staring at the drone during the flight. 20% of the participants did not follow the instructions displayed in the web application when removing items from the drone. Indeed, several users read the instructions in advance to keep both hands free to operate the drone. 48% did not know what to do with their portable device while operating the drone. 8.5% of the participants stopped using the web application and were unable to remove the package from the drone without help from the observer. Finally, only 6% of participants ensured a safe space around the drone before take-off. Moreover, we could observe 44 non-participants in the test walking less than 3 metres away from the drone prior to take-off. To achieve flawless unloading of the package and safe take-offs, we propose to complement the current visual tutorial with voice instructions that users will find convenient to follow [20].

The video analysis revealed that 20% of the users lost time because they were not following the instructions correctly, while 7% spent time taking photos of the drone before removing the parcel. The variable ground time at the recipient location highlights the need for some form of audio support to speed up the drone unloading and return process.

B. Results of the Survey

To gather further feedback, recipients were asked to fill an anonymous survey, which appeared on the portable device after pressing the take-off button. The survey was completed by 84% of the participants, and contained nine closed, and one open question (Fig. 6).

The majority of participants (92%) were between the ages of 20 and 40 and the remaining 8% were between 40 and 60. The survey revealed a largely positive evaluation of Dronistics,

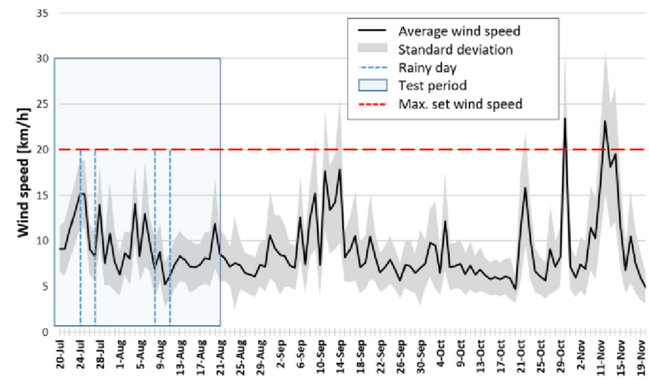

Fig. 7. Wind speed average (black line) and standard deviation (grey area) measured during four months. The test period is highlighted by the blue rectangle. The blue dashed lines show the rainy days during the tests period. The red dashed horizontal line shows the maximum value of the wind speed above which flights were restricted. During four months of wind measurements 94% were flyable days.

the average answers to the questions were graded above four and half points on a five-point scale Participants indicated that the procedure to order items and the recipient web application were easy to understand and to use. They felt that handling the drone was not difficult and that the parcel was easy to retrieve. The majority of people felt safe next to the drone and would request drone delivery again.

The open question ("Additional comments") revealed the following comments and suggestions to improve the system:

1) Messages on the laptop display were hard to see due to sunlight reflection. Use of a smartphone was recommended (1 recipient).
2) The drone take-off and turn during flight was too aggressive and scared participants. Use of a buzzer was proposed to signal the moment when the drone takes off. Smoother change of direction during the flight should be implemented to be less aggressive and frightening (3 recipients).
3) During parcel removal, the cage tended to close. Thus, a system to keep the cage open while removing a parcel was recommended (1 person).
4) It was hard to open the cage and hold the phone to watch the tutorial how to operate the drone (1 person).
5) Older smartphones had a problem to display the web app interface properly (1 person).
6) The Wifi signal was very weak at the recipient location (1 person). Not every portable device has enabled internet connection.

Furthermore, we received additional spoken comments from people who did not take part in the delivery tests. Three people from a nearby cafeteria and the library complained about the noise created by the drone. The person from cafeteria complained about the noise during take-off and landing procedure. The students heard the noise through open roof vents of the library while the drone was flying close by.

C. Weather Conditions

Wind speed was monitored with an anemometer installed on a building next to the recipient location. It was acquired at 1 Hz between 9 am and 4 pm during the test period and the following three months (Fig. 7).

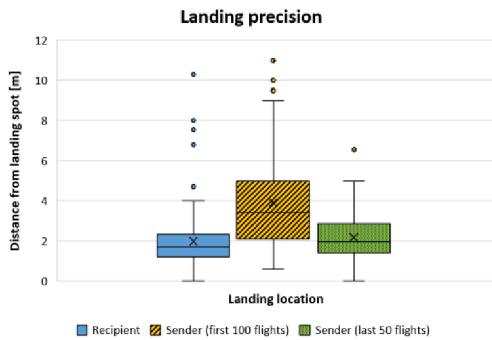

Fig. 8. The plot shows measured distances between the desired landing spot and the effective landing position at the sender and recipient locations. The first box plot presents average landing error at the recipient location. The second box plot presents average landing error at the sender location measured during the first 100 deliveries and the third box plot presents average landing error for the last 50 deliveries. During the last 50 deliveries the coordinates of the landing spot in the sender's location were fixed.

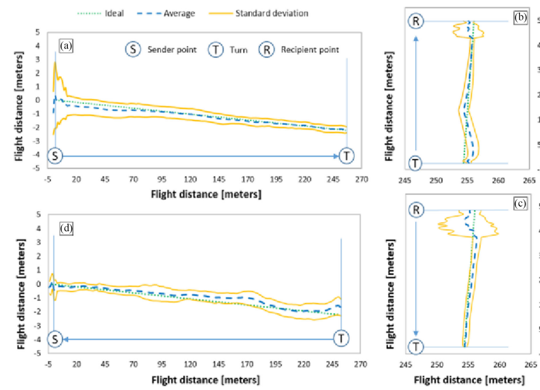

Fig. 9. The mean flight paths of the drone. (a) From sender location to turning point, (b) from turning point to recipient location, (c) from recipient location to turning point, (d) from turning point to sender location. Green dotted lines represent the desired path between waypoints. Blue dashed lines represent averaged values (n = 50). Yellow lines represent the standard deviation (n = 50).

As explained in Section IV the speed of the drone was limited to 6 m/s. Thus, we set the maximum wind speed to 5.5 m/s (20 km/h) for drone delivery to withstand headwinds. During the field test period, the wind never exceeded the maximum allowable speed. During the additional three months' monitoring period we observed only two days when the average speed was above 20 km/h and five days when wind gusts exceeded this threshold. This accounts for a total of 8% of the three-month period. Additionally, there were four days when we could not fly the drone due to heavy rainfall during the field test period.

Despite these precautions, wind gusts that were undetected at the recipient's location led the drone to crash into a tree near the sender's location on two occasions. These two incidents highlight the need for additional wind sensors placed near landing sites or additional control algorithms to improve stability during wind gusts. It should however be noted that the cage successfully protected the drone and its cargo during the collision.

D. Flight Data

Delivery in cluttered environments such as cities or university campuses requires precise landing to prevent accidental landing on pedestrians, cars, buildings, or trees. In these experiments, the drone used only GPS signals to estimate its location. To determine the precision of our drone, we measured the distance between the desired landing spot and the effective landing position at the sender and recipient locations. The recipient landing spot was located in an open area (maps in Figs. 4 and 5) more than 30 metres away from buildings. The sender landing spot was positioned between two buildings, 8 and 12 metres high respectively, and 10 metres away from each one (maps in Figs. 4 and 5). Moreover, two trees with heights of 5 and 10 metres arelocated,10 metres away from the landing spot.

The drone was given the precise coordinates of the recipient location, but used its own GPS estimate of the sender coordinates at take-off for the return landing. The average landing error at the recipient location was 2 metres with a standard deviation of 2 metres (Fig. 8). The average landing error measured at the sender location during the first 100 deliveries was 4 metres with a standard deviation of 5 meters. We hypothesise that this higher error was caused by a poor estimation of the sender's coordinates by the on-board GPS at take-off time, due to signal reflections between nearby buildings, and was further increased by the estimation error during the return landing. We thus fixed the coordinates of the landing spot in the sender location for the last 50 flights, which reduced the average landing error to 2.2 metres with a standard deviation of 2.2 metres. Overall, these results show that GPS guidance may not be sufficient for reliable last-cm, person-to-person delivery in dense environments. For this type of operation, drones should be equipped with additional solutions for precise vertical take-off and landing, such as IR beacons placed on the ground, RTK GPS, or vision-based navigation, which, unlike the previous two solutions, requires no additional hardware on the ground.

We also analysed the precision of the drone path. Here, we present flight path data from the last 50 flights with the hard-coded coordinates of the sender location. As shown in Fig. 9, the average flight path (blue dashed line) follows the ideal path (dotted green line), except for the geographical location where the drone performed a sharp 90-degree turn. The data indicates that the drone systematically overshot and corrected its trajectory, suggesting that its speed should be reduced ahead of sharp turns or the control parameters of the waypoint navigation algorithm should be better adapted to sharp turns.

The standard deviation is presented by the continuous yellow line, and indicates small variations about the desired trajectory. Thus, we can conclude that flights using GPS are more precise than landing at both locations. Furthermore, we observed large deviations during take-off at the recipients' location. This behaviour was caused by a malfunction of one of the electronic speed controllers (ESC), which started one of the four motors a few milliseconds later causing the drone to deviate from the planned path. This malfunction occurred randomly and was solved by replacing the hardware component.

During flight tests, we experienced two unexpected falls to the ground from 5 and 10 metres, respectively, occurring after take-off. Both were caused by disconnection of the battery power connectors. In both cases, the cage was fractured, and the holder for the autopilot and the companion computer were broken. Additionally, following the 10 m fall, the 200 g cargo damaged the box and fell out onto the ground while the box remained attached to the cage. These experiments indicate the need to use reliable connectors and components, and to reinforce the inner box.

VI. Conclusions

This article presents an integrated software and hardware system for last-centimetre drone delivery between people and for business-to-customer services. The results of the flight tests indicate the service's feasibility, and its positive acceptance, at least among members of a technical research institution. The behavioural analysis of the user interaction, the analysis of the flight data, and the few technical problems point to areas of improvement presented below, which could be useful for future improvements and other drone delivery services.

Future work will focus on enhancing user interaction and drone guidance. For instance, we are incorporating a small speaker for voice instructions as a complement to the photo tutorial. These will help recipients to operate the drone when bright sunlight makes it hard to see the screen and will free both hands for retrieving the package. A loud buzzer will be installed to signal the landing and taking off of the drone. Once autonomous flight Beyond Visual Line of Sight (BVLOS) authorisation is received [21], the flight altitude will be increased to reduce the noise perceived from the ground. Additionally, other techniques for noise reduction will be studied and implemented in order to improve user acceptance.

Furthermore, the guidance, control, and navigation algorithms will be adjusted to achieve smoother flight during take-off and sharp turns. Additional guidance systems must also be considered for take-off and landing between tall structures. Multiple weather stations will be required to more precisely estimate local wind conditions between buildings where strong air tunnels can form and disturb the flight, and additional research in wind-resilient control algorithms is warranted. Further tests of the sender's behaviour could be conducted to verify the ease of deploying the cage.

Despite current autonomous BVLOS flight restrictions in public areas [18], it is easier to receive authorisation for such flights on private and restricted areas such as campuses of universities or large companies. This study has been the first application of our last-centimetre aerial delivery service. Future implementations of the system may enable new delivery services between small businesses and customers (B2C) and directly between customers. Moreover, aerial deliveries over short range could also cut emissions [22]. Finally, last-centimetre delivery may become an integral part of the "sharing economy" [23] where individuals borrow or rent assets owned by someone else.

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