

Motion Planning for Physical Contact-based Interaction with a Flapping-wing Drone

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Abstract—Flapping-wing drones have attracted significant attention due to their biomimetic flight, with numerous studies focusing on their wing structure and control methods. They are considered more human-friendly due to its characteristics such as low noise and flexible wings, making them suitable for human-drone interactions. However, few studies have explored the practical interaction between humans and flapping-wing drones. In this study, we propose an interaction system in which a flapping-wing drone performs a palm landing motion on a human hand. To achieve a safe approach toward humans, we design a trajectory planning method that considers both physical and psychological factors of the safety such as the drone's velocity and distance from the user. We implement this trajectory and conduct experiments to evaluate the system's performance and safety. The results demonstrate that our approach enables safe and smooth hand landing interactions. Considering the wide range of applications for hand-landing, it can be said that this study plays a significant role in the development of human-friendly drone interaction systems.

I. INTRODUCTION

In recent years, extensive research has been conducted on Human-Drone Interaction (HDI), exploring various applications. In particular, physical contact-based interaction between drones and humans has gained increasing attention, as it has the potential to expand the scope of drone applications[1], [2]. However, ensuring physical and psychological safety during physical contact has been a significant challenge, especially when using conventional propeller-driven drones. The rapid rotation of propellers poses a potential risk of injury, making it difficult to design safe and natural interactions. Additionally, the high-frequency noise and mechanical appearance of propeller drones often induce psychological discomfort, further limiting their acceptance in close human proximity[3], [4] . To address these issues, previous studies have made proposals such as safeguard mechanisms to cover the drone body[4], [5], drones that has an familiar appearance to human[4], emotion encoding[6], and bio-inspired propellers that make less noise[7].

In contrast, flapping-wing drones, inspired by the flight of birds and insects, offer several inherent advantages that make them particularly suitable for physical contact-based interaction[8]. First, the soft and oscillatory motion of the wings minimizes the physical impact during contact, greatly enhancing physical safety. Second, flapping-wing

drones produce more natural sound compared to propeller-driven drones, reducing psychological discomfort during interaction. Third, the biomimetic appearance and motion of flapping-wing drones evoke a sense of familiarity and warmth, promoting more natural and engaging human-drone interaction.

Despite these promising characteristics, most existing research on flapping-wing drones has primarily focused on their memchanical characteristics such as aerodynamics, wing design, and flight control[9], [10], [11], with little attention given to research on the methodology for them to interact with humans in a physically and psychologically safe way, especially in scenarios involving direct physical contact. To the best of our knowledge, no prior study has specifically investigated the design and implementation of physical contact-based interaction system using flapping-wing drones. This presents a significant research gap in leveraging the unique properties of flapping-wing drones to enhance the quality of human-drone interaction.

To accomplish physical contact-based interaction, it is essential not only to focus on the right moment of contact but also to consider the entire interaction process, including the motion planning and control strategy. Studies has already been conducted on the motion planning of drones during non-contact interaction with humans[12]. However, the research on the motion planning during physical contact is still limited.

Thus, in this study, we propose an interaction system in which a flapping-wing drone performs a palm landing motion on a human hand, enabling direct physical contact in a safe and natural manner. To achieve this, we design a trajectory planning method that considers both physical and psychological safety factors to facilitate safe approaches. We implement this method on a flapping-wing drone and conduct real-world experiments to evaluate its palm landing success rate and viability.

We focus on palm landing because enabling palm landing has several potential advantages described as follows.

- 1) It allows environment-adaptive interaction. In crowded or spatially constrained environments, landing on a fixed surface is often impractical. However, by utilizing the human body as a dynamic landing platform, the drone can overcome spatial limitations and operate more flexibly. This approach is particularly useful in urban scenarios, public transportation, or remote field operations.
- 2) It contributes to energy efficiency enhancement. Drones have limited battery capacity and typically

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consume significant energy when hovering. By landing on a human palm during idle periods, the drone can conserve energy and extend its operational time. This energy-efficient operation is critical for long-term service tasks, search and rescue missions, or continuous monitoring operations.

- 3) palm landing enhances personalized companion interaction. By physically landing on a human palm, a drone can provide pet-like interaction, evoke emotional attachment, or facilitate social engagement. This is particularly promising for children, the elderly, or individuals with social isolation, where physical interaction fosters a stronger sense of companionship.

These advantages highlight the potential of palm landing as a key interaction modality for flapping-wing drones, enabling a wide range of applications in various scenarios.

The main contributions of this work can be summarized as follows:

- 1) We propose a human-friendly interaction system utilizing a flapping-wing drone, focusing on trajectory planning.
- 2) We develop an intuitive device system for drone interaction.
- 3) We verify the proposed model using an actual drone.

The remainder of this paper is organized as follows. The basic mechanical characteristics and control method of flapping-wing drone is introduced in Section II. The motion planning based on physical and psychological factors is presented in Section III, followed by the experimental results in Section IV before concluding in Section V.

II. MODELING

In this section, we describe the dynamic model and control of a basic flapping-wing drone.

A. Dynamic Model

There are various types of flapping-wing drones, and we focus on a tailless aerial robotic flapper model[13], as shown in Fig. 1. The drone is mounted with four motors: two motors for thrust (m_1, m_2), one motor for pitch control (m_3), and one motor for yaw control (m_4).

The longitudinal dynamics of the flapper has been studied in the previous work [14], and we follow the same model in this paper, which is written as follows:

$$\{CoG\} \mathbf{f}_i = \lambda_i \{CoG\} \mathbf{u}_i, \quad (1)$$

$$\{CoG\} \mathbf{u}_i = \{CoG\} R_{\{F_i\}}(\phi_i, \theta_i) \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad (2)$$

where $\{CoG\} R_{\{F_i\}}(q, \phi_i, \theta_i)$ is the rotation matrix of the motor frame $\{F_i\}$ w.r.t. the frame $\{CoG\}$, and λ_i is the thrust coefficient of the m_i . ϕ_i and θ_i are rotational angles of the m_3 and m_4 , respectively. The total force and torque generated by m_1 and m_2 can be written as:

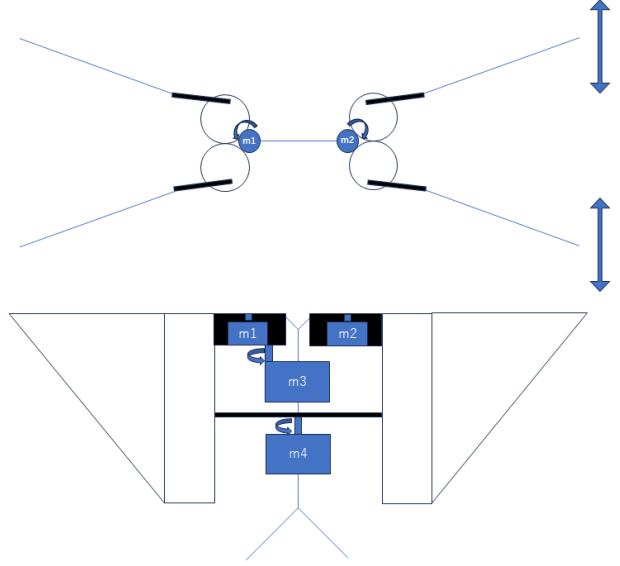


Fig. 1: The mechanical structure model of a tailless aerial robotic flapper. It has motors for thrust (m_1, m_2), a motor for pitch control (m_3), and a motor for yaw control (m_4).

$$\begin{bmatrix} \{CoG\} \mathbf{f}_\lambda \\ \{CoG\} \boldsymbol{\tau}_\lambda \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^2 \{CoG\} \mathbf{f}_i \\ \sum_{i=1}^2 \{CoG\} \mathbf{p}_i \times \{CoG\} \mathbf{f}_i \end{bmatrix} = Q \boldsymbol{\lambda}, \quad (3)$$

$$Q = \begin{bmatrix} \{CoG\} \mathbf{u}_1 & \{CoG\} \mathbf{u}_2 \\ \{CoG\} \mathbf{p}_1 \times \{CoG\} \mathbf{u}_1 & \{CoG\} \mathbf{p}_2 \times \{CoG\} \mathbf{u}_2 \end{bmatrix}, \quad \boldsymbol{\lambda} = [\lambda_1 \quad \lambda_2]^T. \quad (4)$$

The whole dynamic model can be written as follows:

$$m^{\{W\}} \ddot{\mathbf{r}}_{\{CoG\}} = \{W\} R_{\{CoG\}} \mathbf{f}_\lambda - mg + \sum_{i=1}^{N_c} \{W\} \mathbf{f}_{c_i}, \quad (5)$$

$$I \dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times I \boldsymbol{\omega} = \boldsymbol{\tau}_\lambda + \sum_{i=1}^{N_c} \{CoG\} \mathbf{p}_{c_i} \times \{W\} R_{\{CoG\}}^T \{W\} \mathbf{f}_{c_i}, \quad (6)$$

where m is the mass of the drone, I is the inertia matrix, $\mathbf{r}_{\{CoG\}}$ is the position of the center of gravity, \mathbf{g} is the gravity vector, \mathbf{f}_{c_i} is the contact force, and \mathbf{p}_{c_i} is the position of the contact point.

B. Control

The control model of the flapping-wing drone is shown in Fig. 2. Based on the dynamics of (5) and (6), we can design a PID controller for the flapping-wing drone. One of the control inputs is the desired force \mathbf{f}_λ^d , which can be written as:

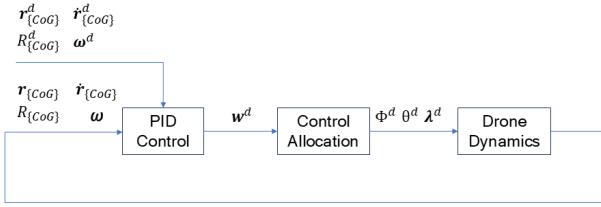


Fig. 2: The PID control model of a flapping-wing drone. It has mot

$$\begin{aligned} \{CoG\} f_\lambda^d = & m^{\{W\}} R_{\{CoG\}}^T \left(K_{f,p} e_r + K_{f,i} \int e_r dt + K_{f,d} \dot{e}_r \right) \\ & + \{W\} R_{\{CoG\}}^T \left(mg - \sum_{i=1}^{N_c} \{W\} f_{c_i} \right). \end{aligned} \quad (7)$$

where $K_{f,*}$, are the PID gain diagonal matrices, and $e_r = \{W\} r_{\{CoG\}}^d - \{W\} r_{\{CoG\}}$ is the position error.

The attitude control follows the part of the control method proposed by [15]:

$$\begin{aligned} \{CoG\} \tau_\lambda^d = & I \left(K_{\tau,p} e_R + K_{\tau,i} \int e_R dt + K_{\tau,d} e_\omega \right) \\ & + \omega \times I \omega - \sum_{i=1}^{N_c} p_{c_i} \times R^T f_{c_i}, \end{aligned} \quad (8)$$

$$e_R = \frac{1}{2} (R^T R^d - (R^d)^T R)^\vee, \quad (9)$$

$$e_\omega = R^T R^d \omega^d - \omega. \quad (10)$$

where $[\star]^\vee$ is the inverse of a skew map, and $R := \{W\} R_{\{CoG\}}$ for convenience. Then, the desired wrench w.r.t the frame $\{CoG\}$ can be summarized as follows:

$$w^d = [\{CoG\} f_\lambda^d \quad \{CoG\} \tau_\lambda^d]^T. \quad (11)$$

III. MOTION PLANNING

To design a motion planning method that minimizes psychological discomfort when a flapping drone approaches a human, we must consider the several factors:

A. Distance

Given the expected size and shape of a flapping drone, we estimate that the minimum acceptable distance falls within a specific range. By maintaining this distance while gradually invading the landing zone, the psychological burden can be minimized. Several studies have investigated the psychological burden imposed by drones depending on their distance from humans using different drone sizes[4], [16], [17], [18]. [16] is a paper focusing on tactile drone interaction using a drone with a wheelbase of 0.92m, which is suitable for palm landing. This paper conducted an experiment in which participants were asked to stop the drone when they felt uncomfortable by using foot (non-contact) and hand (contact)

methods. The results show that the maximum stop distance was approximately 1.25m, which means that, if the drone needs to approach closer than this distance, it should be done in psychologically safe manners such as gradually decreasing the speed or using a trajectory that does not directly approach the user so that the user does not feel threatened.

Moreover, the study [16] also shows that even the minimum stop distance was above 0.30m, which means that the drone should not approach the user closer than this distance. This indicates that physical contact should occur outside this range to guarantee physical and psychological safety.

B. Altitude

In the study [16], the height was set to enable a convenient way of tactile interaction by allowing the participants to slightly look down to the quadrotor. We follow this setting because then users do not need to move their head to look up to the drone and are able to simultaneously observe both the drone and their own hand, which leads to easier adjustments of the hand position while the drone is approaching. Assuming that users lift their hand to the height of their elbow for palm landing, the drone should be positioned at the height of between the elbow and the eye level.

C. Approach Direction

As noted in [16], the approach direction of the drone affects the psychological burden. The study shows that the participants felt most uncomfortable when the drone approached them from the back because they could not see the drone. Therefore, the drone should approach the user from the front or side to minimize the psychological burden.

D. Velocity

To assess the appropriate velocity of the drone, we need to consider the human perception of speed of an approaching object. The study [19] shows that the drivers' perception of the speed of an foregoing vehicle follows Weber's Law:

$$k \frac{\Delta W}{W} = \Delta s \quad (12)$$

where W is the measurable stimuli, s the intensity of sensation, Δ the increment of physical quantity (W) and sensation intensity (s), and k the coefficient. In the study [19], W corresponds to the the distance between the cars and s to the speed of the driver's car. We assume that the same law can be applied to the perception of the speed of an approaching drone by regarding the distance between the drone and the user as W and the perceptive speed of the drone as s . This assumption explains the result of the previous study on perceived safety of drones [12], which shows the trend that larger distances are perceived as overly safe while a fast-moving drone close to participants is perceived as less safe than needed, because we can consider from the law that the participants perceive the speed of the drone as too slow due to the large distance between the drone and the participants and as too fast due to the short distance between the drone and the participants. Denoting the speed

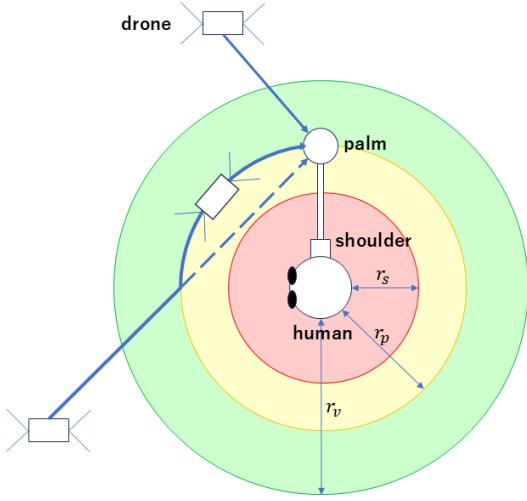


Fig. 3: Proposed motion planning for flapping drone approach. It has 4 domains which are separated by the distance from the user. Different strategies are applied to drone motion in different domains.

of the drone as v , the distance between the drone and the user as d , and time as t , we can derive the following equation:

$$k \frac{v \Delta t}{d} = \Delta s \quad (13)$$

To secure the psychological safety, the drone should approach the user keeping Δs constant. Thus, the speed can be calculated as follows:

$$v = \frac{k' d}{\Delta t} \quad (14)$$

where k' is a constant. We let $k' = 0.2$ in the present study.

E. Trajectory Design

Based on the above findings, we propose the following motion planning method, as illustrated in Figure 3. We divide the approach trajectory into four domains based on the distance between the drone and the user r .

1) $r > r_v$

The drone is far from the user and approaches the palm straight at a constant speed. We let $r_v = 1.25$ based on III-A.

2) $r_v \geq r > r_p$

The drone is close enough to the user to be possibly perceived as unsafe, so it gradually decreases its speed by following (14).

3) $r_p \geq r > r_s$

The drone is inside the circle with the radius of user's arm length r_p centered at the user's chest. To maintain a certain distance from the user, the drone moves along the circle toward the user's palm while decelerating. On this path, the velocity of the drone towards the user's chest is always zero, which means $\Delta s = 0$ in (14) and minimizes the threat to the perceived safety.

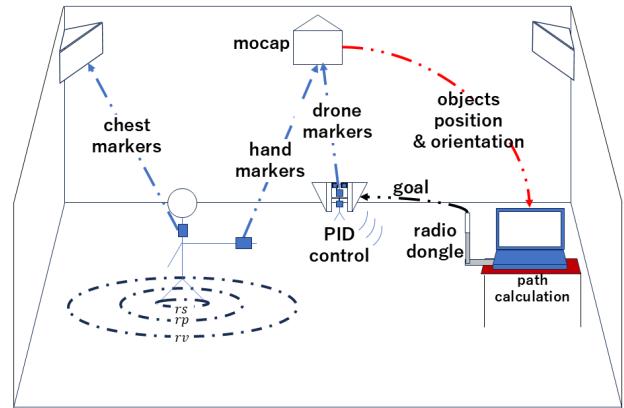


Fig. 4: Overall system configuration.

4) $r \leq r_s$

If the drone is within this range, it is too close to the user and has a high risk of collision. Thus, the drone avoids the user by moving away from the user's body. Moreover, if the palm is within this range, the drone stays still and waits for the user to move their palm to the landing position outside the range so that the drone will not intrude the domain. We let $r_s = 0.30m$ based on III-A.

IV. EXPERIMENT

In this section, we first describe the testbed and then present the results of the experiments.

A. Testbed

1) Overall system: Fig. 4 illustrates the overall experimental system configuration. The system consists of a motion capture (MoCap) system, a flapping-wing drone, a user wearing devices, and a PC for trajectory planning and control. The MoCap system tracks the 3D positions and orientations of the user's chest, palm, and the drone in real time. We place 8 Optitrack Prime 13 cameras on the 4 corners and 4 sides of the room. The user wears chest-mounted and wrist-mounted markers allowing the system to capture intuitive control gestures. The PC processes the positional data and calculates the drone's optimal approach path toward the user's palm while maintaining a safe distance. The computed path is transmitted to the drone via a radio dongle, ensuring real-time control. The drone goes to the newest goal received from the PC using PID control, adjusting its motion dynamically based on feedback from the MoCap system.

Then, we describe the drone used in the experiment and the interface for control in detail.

2) Flapping Drone: Flapper Nimble+ used in the experiment, shown in (5a), is a bioinspired flapping-wing drone by FLAPPER DRONES compatible with the Crazyflie software, which is an open-source platform for research and development of quadcopters produced by Bitcraze AB. As shown in 5b attached four motion capture markers on its legs for tracking its position and orientation.

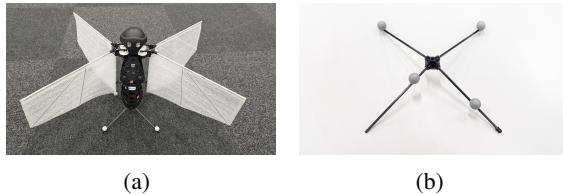


Fig. 5: (a) Flapper Nimble+ drone, (b) its leg with motion capture markers.

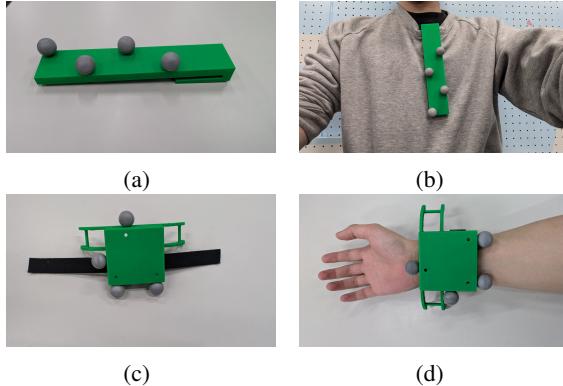


Fig. 6: (a) Chest-mounted device, (c) wrist-mounted device for controlling the state of flapping drone. (b, d) the attachment of the devices.

3) Interface For Control: As noted in III-3, the drone has to change its behavior according to the position of the user’s palm. To facilitate intuitive control, we designed a wearable interface consisting of:

- A chest-mounted device shown in (6a)
- A wrist-mounted device shown in (6c)

Both devices were fabricated using a Bambu Lab X1-Carbon 3D printer. With these devices, we acquire the user’s palm position and orientation from the motion capture system and calculate the desired drone behavior based on the user’s palm position. This interaction design only requires arm bending and stretching to switch the state of the drone and thus enables a seamless and intuitive approach control.

B. Results and Analysis

1) Trajectory Mapping: We mapped the actual flight trajectory and orientations of the drone, and attached drone state labels to the corresponding positions. The red points in Fig. 7a indicates the actual positions of the drone during the approach and the blue points the target positions. The arrows stemming from the red points indicate the orientation of the drone. The blue points start when the drone state becomes “APPROACH” as shown in Fig. 7a. It can be observed that the drone closely follows the planned trajectory. Furthermore, its orientation consistently remains directed towards the user’s chest and the drone successfully approaches the user’s palm.

2) Velocity Profile: We analyzed the velocity profile of the drone from the beginning of the approach to the end of the palm landing ,as illustrated in Fig. 7b, to verify the behavior

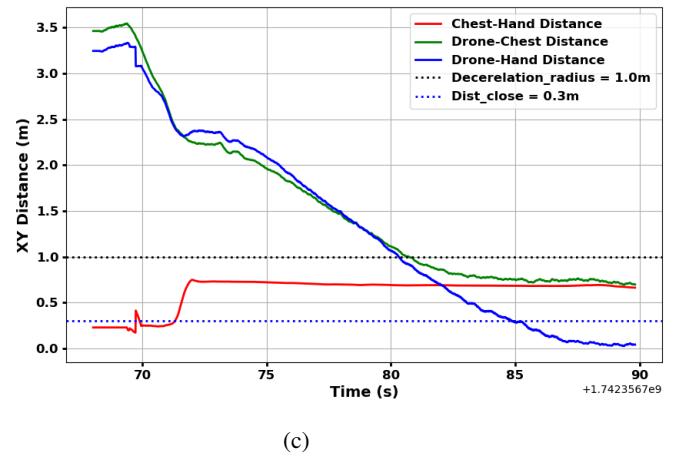
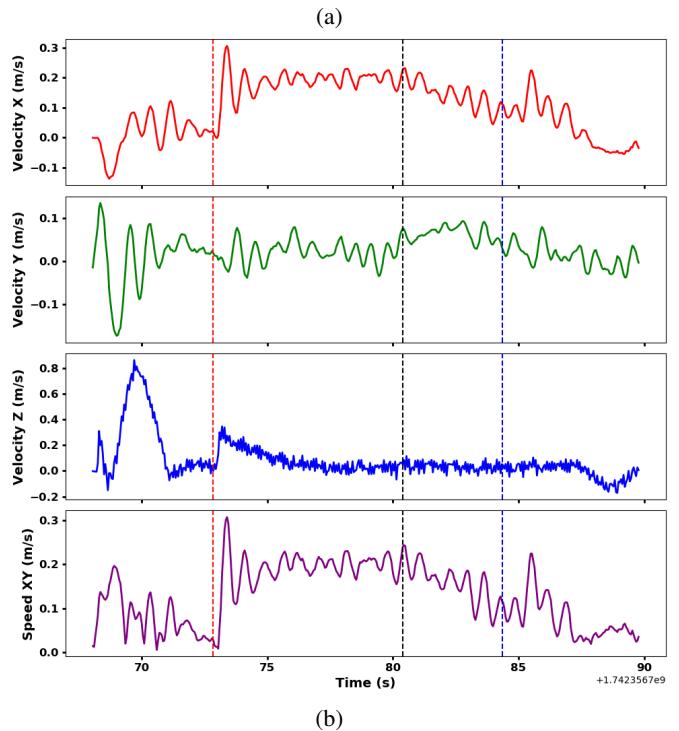
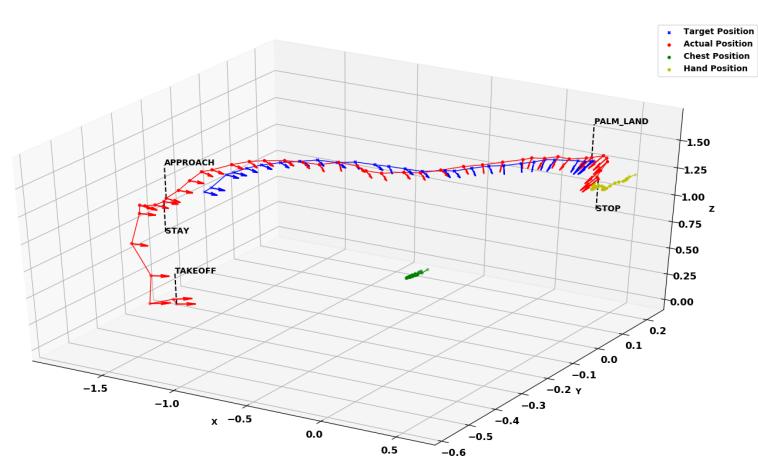


Fig. 7: Results of the experiment. (a) Trajectory and orientations of the drone during the approach. (b) Velocity profile of the drone during the approach. (c) Distance between the user’s chest and the drone during the approach.

of the drone during the approach. The vertical dotted red line indicates the approach start time, the black line the time when the drone starts to decelerate, and the blue line the time when k' changes from 0.2 to 0.5. You can see in Fig. 7b that between the red and black lines, XY speed oscillates around a constant value. After the black line, the drone decelerates and the XY speed successfully decreases. You can see a spike right after the blue line, which is considered to be due to the acceleration caused by the change in k' as expected.

3) Distance Between Chest and Drone: A distance-time graph was generated to verify whether the drone maintained a safe distance from the user during the experiment. As shown in Fig. 7c, the chest-drone distance and the drone-hand distance start decreasing when the chest-hand distance is above 0.3m, the drone successfully keeps out of the chest-hand range, which means that the user can interact with the drone at the point where they want to without any collision. Furthermore, the drone-hand distance gradually and smoothly decreases to zero without any overshoots, which enables smooth and safe hand-landing.

V. CONCLUSIONS

In this paper, we proposed a motion planning method for physical contact-based interaction with a flapping-wing drone based on different perspectives relevant to the user's safety. We demonstrated that the proposed method can generate a safe and smooth trajectory for the drone to approach a user's palm while avoiding collisions and maintaining a safe distance. A remained task is users' subjective evaluation of the psychological impact of the drone's motion. To achieve truly human-friendly interaction, we need to consider not only the safety but also the psychological comfortableness of the user. We believe this work is a step toward the realization of the society where drones and humans can coexist in harmony without any frustration.

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The preferred spelling of the word acknowledgment in America is without an e after the g. Avoid the stilted expression, One of us (R. B. G.) thanks ... Instead, try R. B. G. thanks. Put sponsor acknowledgments in the unnumbered footnote on the first page.

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