Preparation of Papers for IEEE Sponsored Conferences & Symposia*

Albert Author[1] and Bernard D. Researcher[2]

Abstract— **Flapping-wing drones have attracted significant attention due to their biomimetic flight, with numerous studies focusing on their wing structure and control methods. Compared to propeller-driven drones, flapping-wing drones are considered more human-friendly, 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 perching motion on a human hand. To achieve a safe approach toward humans, we design a trajectory planning method that considers both physical and psychological human factors. We implement this trajectory and conduct experiments to evaluate the system's performance, including success rate and user perception. The results demonstrate that our approach enables safe and effective perching interactions. To the best of our knowledge, this study is the first to investigate physical contact interactions between humans and flapping-wing drones.**

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 such as [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 methodlogy 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.

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 human factors to facilitate safe and comfortable approaches. We implement this method on a flapping-wing drone and conduct real-world experiments to evaluate its palm landing success rate and valiability.

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 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 indi-

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[1]Albert Author is with Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, 7500 AE Enschede, The Netherlands albert.author@papercept.net

[2]Bernard D. Researcheris with the Department of Electrical Engineering, Wright State University, Dayton, OH 45435, USA b.d.researcher@ieee.org

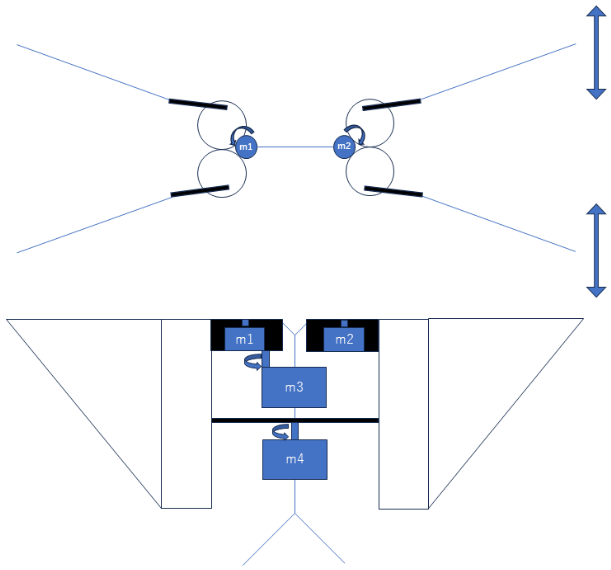

Fig. 1. The mechanical structure model of a flapping-wing drone. It has motors for thrust (m1, m2), a motor for wing orientation (m3), and a motor for yaw control (m4).

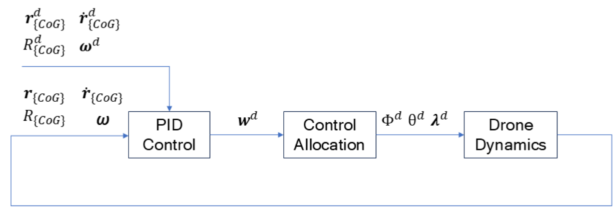

Fig. 2. The PID control model of a flapping-wing drone. It has mot

viduals 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 mecanical characteristics and contorl 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 explanation of the device system for the interaction in Section IV. We then show the experimental results in Section V before concluding in Section VI.

II. MODELING

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

A. Dynamic Model

Based on the model depicted in Fig. 1, the threedimensional force f_i generated by m_i can be written as:

$$^{\{CoG\}}\boldsymbol{f_i} = \lambda_i {}^{\{CoG\}}\boldsymbol{u_i}, \tag{1}$$

$$^{\{CoG\}}\boldsymbol{u_i} = {}^{\{CoG\}}R_{\{F_i\}}(\phi_i, \theta_i) \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \tag{2}$$

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:

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

$$Q = \begin{bmatrix} ^{\{CoG\}}\boldsymbol{u_1} & ^{\{CoG\}}\boldsymbol{u_2} \\ ^{\{CoG\}}\boldsymbol{p_1} \times {}^{\{CoG\}}\boldsymbol{u_1} & ^{\{CoG\}}\boldsymbol{p_2} \times {}^{\{CoG\}}\boldsymbol{u_2} \end{bmatrix}$$
$$\boldsymbol{\lambda} = \begin{bmatrix} \lambda_1 & \lambda_2 \end{bmatrix}^T. \tag{4}$$

The whole dynamic model can be written as follows:

$$m^{\{W\}}\ddot{\boldsymbol{r}}_{\{CoG\}} = ^{\{W\}} R_{\{CoG\}}\boldsymbol{f}_\lambda - m\boldsymbol{g} + \sum_{i=1}^{N_c} {}^{\{W\}}\boldsymbol{f}_{c_i}, \tag{5}$$

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

where m is the mass of the drone, I is the inertia matrix, $\boldsymbol{r}_{\{CoG\}}$ is the position of the center of gravity, $\boldsymbol{g}$ is the gravity vector, $\boldsymbol{f}_{c_i}$ is the contact force, and $\boldsymbol{p}_{c_i}$ 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 $\boldsymbol{f}^d_\lambda$, which can be written as:

$$\begin{aligned} ^{\{CoG\}}\boldsymbol{f}^d_\lambda = \;& m^{\{W\}}R^T_{\{CoG\}}\left(K_{f,p}\boldsymbol{e_r} + K_{f,i}\int \boldsymbol{e_r}\,dt + K_{f,d}\dot{\boldsymbol{e}}_{\boldsymbol{r}}\right) \\ & + {}^{\{W\}}R^T_{\{CoG\}}\left(m\boldsymbol{g} - \sum_{i=1}^{N_c} {}^{\{W\}}f_{c_i}\right). \end{aligned} \tag{7}$$

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

The attitude control follows the part of the control method proposed by [12]:

$$
\begin{aligned}
{}^{\{CoG\}}\boldsymbol{\tau}_{\lambda}^{d} &= I\left(K_{\tau,p}\boldsymbol{e}_R + K_{\tau,i}\int \boldsymbol{e}_R\,dt + K_{\tau,d}\boldsymbol{e}_{\boldsymbol{\omega}}\right) \\
&\quad + \boldsymbol{\omega}\times I\boldsymbol{\omega} - \sum_{i=1}^{N_c}\boldsymbol{p}_{c_i}\times R^T\boldsymbol{f}_{c_i}, \qquad (8)
\end{aligned}
$$

$$
\boldsymbol{e}_R = \frac{1}{2}\left(R^T R^d - (R^d)^T R\right)^{\vee}, \qquad (9)
$$

$$
\boldsymbol{e}_\omega = R^T R^d \boldsymbol{\omega}^d - \boldsymbol{\omega}. \qquad (10)
$$

Then, the desired wrench w.r.t the frame $\{CoG\}$ can be summarized as follows:

$$
\boldsymbol{w}^d = \left[{}^{\{CoG\}}\boldsymbol{f}_{\lambda}^{d} \quad {}^{\{CoG\}}\boldsymbol{\tau}_{\lambda}^{d}\right]^T. \qquad (11)
$$

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 useing different drone sizes[4], [13], [14], [15]. [13] 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 overall stop distance was $\bar{x}$ = 0.63m (σ = 0.33m), 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 [13] also shows that the average distance at which participants stopped the drone using their hands was $\bar{x}$ = 0.47m (σ = 0.09m). This indicates that physical contact should occur outside this range to guarantee physical and psychological safety.

B. Altitude

According to [**?**], an appropriate altitude for approach is around X meters, as excessively high approaches can lead to discomfort.

C. Approach Direction

As indicated in [13], drones positioned behind a person induce greater psychological burden. Therefore, the drone should approach either from the user's front or from the left side to ensure comfort.

Fig. 3. Proposed trajectory for flapping drone approach.

D. Velocity

The perception of speed follows Weber's Law: at closer distances, small changes in distance appear faster, whereas at greater distances, motion perception is less sensitive [**?**].

Thus, slower speeds are preferable at closer distances. Studies on driver perception of approaching vehicles [**?**] suggest that gradual deceleration is beneficial, as it reduces overshooting when the drone reaches the hand position.

To further decrease the sense of intrusion, it is preferable for the drone to descend onto the palm from a direction perpendicular to the user's line of sight. This necessitates dividing the trajectory into distinct approach phases.

E. Trajectory Design

Based on the above findings, we propose the following trajectory, as illustrated in Figure 3.

IV. USING THE TEMPLATE

Use this sample document as your LaTeX source file to create your document. Save this file as **root.tex**. You have to make sure to use the cls file that came with this distribution. If you use a different style file, you cannot expect to get required margins. Note also that when you are creating your out PDF file, the source file is only part of the equation. *Your TEX $\rightarrow$ PDF filter determines the output file size. Even if you make all the specifications to output a letter file in the source - if your filter is set to produce A4, you will only get A4 output.*

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TABLE I
AN EXAMPLE OF A TABLE

One	Two
Three	Four

Fig. 4. Inductance of oscillation winding on amorphous magnetic core versus DC bias magnetic field

Figure Labels: Use 8 point Times New Roman for Figure labels. Use words rather than symbols or abbreviations when writing Figure axis labels to avoid confusing the reader. As an example, write the quantity Magnetization, or Magnetization, M, not just M. If including units in the label, present them within parentheses. Do not label axes only with units. In the example, write Magnetization (A/m) or Magnetization A[m(1)], not just A/m. Do not label axes with a ratio of quantities and units. For example, write Temperature (K), not Temperature/K.

V. CONCLUSIONS

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

APPENDIX

Appendixes should appear before the acknowledgment.

ACKNOWLEDGMENT

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.

References are important to the reader; therefore, each citation must be complete and correct. If at all possible, references should be commonly available publications.

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