Model-Based Lateral Tracking for Bird-Size Ornithopters in Perching Scenario

Andres Rosa[1], Ernesto Sanchez-Laulhe[2] and Anibal Ollero[1], *Fellow, IEEE*

***Abstract*— An improved tracking method for ornithopters in perching scenario is presented. Based on previous works, this article develops a model-based approach for the lateral controller of the ornithopter. The insights into the dynamics provided by the simplified model allow the ornithopter to track the target point in an indoor confined space with motion capture system feedback. The lateral control follows a cascade architecture to transform the actuator movement, which for this kind of platform is the deflection of the vertical tail, into an effective trajectory tracking in the horizontal plane. Results show an improvement in the accuracy of the perching maneuver, reducing the errors in the horizontal plane from the perching position to the target point, the center of the branch in this case. In addition, the improved lateral control allows the ornithopter to reach the perching objective from different initial positions and directions, so it can perform a real 3D perching, compared to the previous experiment where the launching direction was aligned with the branch. This new controller can also be implemented for 3D trajectory tracking, leading to a complete ornithopter-based autopilot architecture.**

***Keywords*: Flapping-wing, Lateral tracking, Ornithopter, Perching, Dynamics.**

I. Introduction

The development of new flapping-wing UAVs has opened new challenges for improving their flight and taking advantage of their unique characteristics. There are already several platforms with proven functionality. Small tailless prototypes, similar to insects and small birds such as hummingbirds, have proven outstanding performance in terms of maneuverability [1], [2]. Trajectory tracking with tailless flapping wing prototypes was achieved with Optitrack feedback in several works [3], [4]. Even small prototypes with wing-tail configurations have also shown trajectory-tracking capabilities in confined spaces [5].

For bigger FWUAVs, the maneuverability becomes more complex. Without hovering capability, bird-size ornithopters must fly forward to maintain stability, reducing the time to correct trajectory errors. In addition, asymmetrical actuations are not present in bird-size FWUAVs, due to the mechanical complexity of the flapping wings. For that reason, lateral control is developed with the tail. There are different tail configurations for FWUAVs. When compared in [6], the conventional tail provided a better performance in terms of control power, even though inverted V-tails are also used as they are more stable.

[1]A. Rosa, and A. Ollero are with the GRVC Robotics Lab., Departamento de Ingeniería de Sistemas y Automática, Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Seville, Spain, (Emails: androsflo@alum.us.es, aollero@us.es).

[2]E. Sanchez-Laulhe is with the Fluid Mechanics group, University of Málaga, Málaga, Spain, (Email: ernesto.slaulhe@uma.es).

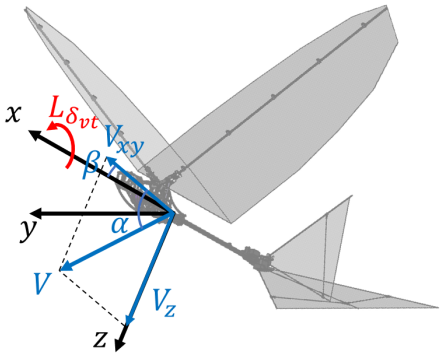

Fig. 1. Roll moment generated by a sideslip angle.

Several platforms use commercial autopilots based on airplane configurations for flight control, showing good performance tracking waypoints in outdoor environments [7], [8]. In [9], Wenfu et al. developed a controller based on FreeRTOS, also showing outdoor experiments to verify their methods. However, the precision of those controllers is limited for confined spaces, where more aggressive maneuvers are required to track waypoints. Indoor experiments, such as perching maneuvers [10], are normally performed by launching the ornithopter in the direction of the target point, so the lateral control is reduced to maintaining the flight direction.

Modeling of flapping wing flight becomes very important for maneuvering in confined spaces. Related works are focused mostly on longitudinal control, from multi-body systems with identified aerodynamic models [11] to rigid body models with simplified aerodynamics [12]. More complex models based on fluid-structure interaction [13] are more precise, although they are too complex to be used in real-time. Simplified models based on unsteady aerodynamics results have already been used for FWUAVs in an indoor environment [14].

However, there are not many works concerning lateral dynamics. The development of 3D models for FWUAV is focused on small tailless platforms, for which the dynamics are completely different [15]. Those works are based on simplified aerodynamics, considering only the averaged aerodynamic forces and neglecting the flapping oscillations. With a similar approach, but for flapping forward flight, a model-based approach is developed in [16] to perform circular trajectories of a radius of approximately 4 m.

The contribution of this paper is a modification of the circular trajectory tracking approach for the lateral tracking

of the FWUAV in a perching scenario, where the precision of the maneuver is essential. The actuation on the tail provides fast control over the roll angle, resulting in aggressive trajectories for changes in the heading of the FWUAV. This approach significantly improves the error for the arrival to the target point of the branch, which is important for performing manipulation tasks after perching. Additionally, the performance of the lateral control is tested by varying the initial position and direction of the ornithopter.

Even though this work is originally focused on improving the lateral tracking of the perching target point, the implementation of the lateral controller can be extended easily for the tracking of several waypoints in the same flight, to design a complete autopilot architecture for FWUAVs.

II. Dynamics and control

In this section, an overview of the dynamics and control of the ornithopter is given. The dynamics can be found more detailed in [14], [16].

A. Dynamics

The mechanism for lateral movements in the FWUAV is quite similar to airplanes. To modify its heading, the ornithopter has to rotate itself in roll ϕ, generating a projection of the lift force in the horizontal plane. The turning radius R is then given by

$$R = \frac{V^2}{g\tan(\phi)}, \tag{1}$$

where V indicates flight velocity and g the gravity acceleration. Note that the velocity is also a significant parameter for the heading rate of the FWUAV. Following the formulation in [14], the velocity can be expressed as a function of the lift coefficient C_L:

$$V = \sqrt{\frac{2mg}{\rho S C_L(\alpha)\cos(\phi)}}, \tag{2}$$

with m the mass of the ornithopter, ρ the air density and S the wing surface. Note that the lift coefficient is expressed as a function of the angle of attack α, which has been proven to be an accurate first approximation in [14]. Then, for low roll angles, the velocity is defined mainly by controlling the angle of attack, which is done by actuating the horizontal tail.

However, the velocity is normally fixed according to other parameters (efficiency, minimal velocity, etc). For that reason, the lateral control is based only on the roll angle control, even though the gains of the controller will vary according to the flight velocity of the maneuver.

The deflection of the vertical tail δ_{vt} is the actuation used to control the roll angle of the FWUAV. However, this deflection does not generate a direct roll moment, being the main difference with airplane controllers where the roll moment is achieved by the ailerons in the wings. When the vertical tail is deflected, it generates a yaw moment, which causes the FWUAV to fly with a certain sideslip angle $\beta = C_{n\delta_{vt}}\delta_{vt}$. The roll moment is then generated as a consequence of the coupling between lateral and directional dynamics. When the incoming aerodynamics velocity has a lateral component a differential lift is created between both wings, resulting in a roll moment, as illustrated in fig. 1. Then, being the dynamics fast, we can define the roll rate as a function of the vertical tail deflection:

$$\dot{\phi} = b_{\delta_{vt}}\delta_{vt}, \tag{3}$$

and the parameter $b_{\delta_{vt}} = 0.7s^{-1}$ is obtained experimentally in [16], where the lateral dynamics are also explained with further details.

B. Control

The control architecture is based on the platform E-Flap [17] developed as part of the GRIFFIN ERC Advanced Grant. In [10], this platform achieved a successful perching maneuver based on three independent PID controllers. The altitude controller proved to be accurate enough for the perching maneuver, reaching the desired height with a small error, even when the height of the branch was modified. At the same time, control of the angle of attack minimized the velocity to reduce the strength of the impact with the branch.

However, the lateral control was limited, as it worked only to maintain the approximate direction. The tracking was performed by defining the straight line between the target and the instantaneous position, which gave the desired heading to be introduced into the controller. Then a singular PID computed the error in the heading and sent the control signal to the vertical tail actuator.

In this work, a new approach is followed. After demonstrating the capability to fly in circles by adding an inner control loop for the roll angle in [16], this controller has been slightly modified to track a target point in the horizontal plane. While the inner loop remains unchanged, the outer loop is substituted by the previous heading controller, which computes the error between the desired and the actual heading.

C. Experimental setup

For the experimental setup, two different cases are considered. First, the precision of the controller is tested in the previous perching scenario, where the launching direction is approximately that of the target point. An automatic launcher is used, providing repeatability in the initial conditions with a speed of $4\,\mathrm{m/s}$ in a straight direction. However, there are uncertainties in the launching due to the electronics delay or the friction in the decoupling from the launcher, which may cause small deviations that the controller should correct. In this first case, the accuracy of both the previous and the improved controller are compared. The second scenario involves the variation of the initial conditions so the controllers have to modify the trajectory to reach the branch. Different initial positions and directions are tested to show the accuracy of both controllers.

All the experiments were conducted in the indoor experimental testbed of the GRVC lab. Attitude and position feedback was provided by a Motion Capture System with

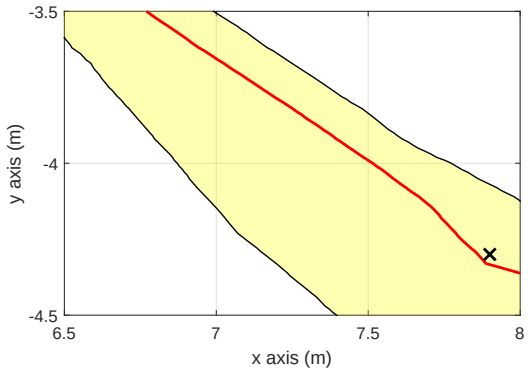

Fig. 2. Precision of perching with previous controller. The red line is the average trajectory and the shadowed area is the trust interval.

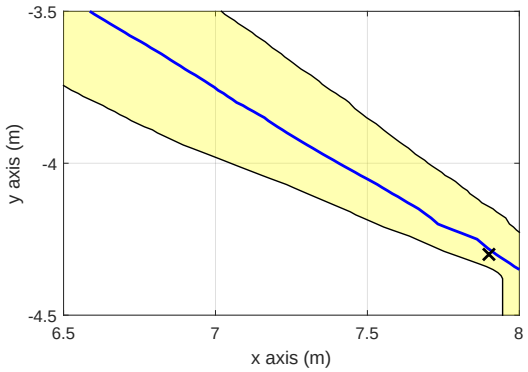

Fig. 3. Precision of perching with the new controller. The blue line is the average trajectory and the shadowed area is the trust interval.

28 cameras at a frequency of 120 Hz. The prototypes used are two different versions of the E-Flap platform. An older version, similar to that in [17] is used for the experiments without the branch, where the controllers were tested. Then, the renewed version with the claw that appears in [10] is used for the perching with the branch.

III. Experimental results

A. Perching experiments

The perching scenario considered is the same from [10]. The branch is positioned in a corner and the FWUAV is launched from the opposite side of the diagonal of the testbed with the direction towards the branch. The goal is to compare the accuracy in the most favorable scenario. The initial position is [-5.7,4.1] m and the target point is [7.9, -4.3] m. The initial heading is computed with both positions, resulting in 31.70^o.

We have carried out around 20 experiments for both controllers. First, we can see the result with the previous controller in fig 2, where the average results show how the ornithopter targets the branch, but with a wide range of errors, as the controller cannot properly correct the deviations due to flight uncertainties. The new controller improves significantly this range of arrival trajectories, as observed in fig. 3. The average arrival trajectory is similar, but the range is narrowed, reducing the uncertainty for perching. The mean and maximum errors are reduced from 0.24 m and 0.48 m with the previous controller to 0.05 m and 0.12 m with the model-based approach.

B. Tracking from different positions

After testing the accuracy of the controller in the most favorable scenario, the tracking of the perching position has been done varying the initial condition. In particular, three cases have been considered. The first two cases are carried out by changing the direction with a similar initial point. In the third case, also the initial point is modified. The point has not been modified. The specific conditions are:

- Case 1: Initial position [-4.97,4.1] m and heading 1.25^o
- Case 2: Initial position [-5.33,-3.39] m and heading 78.71^o

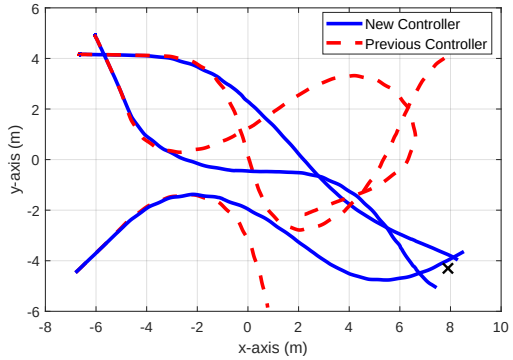

Fig. 4. Trajectories for both controllers with different initial conditions

- Case 3: Initial position [-6.33,4.01] m and heading -79.01^o

The trajectories obtained can be observed in fig. 4. In both three cases, the previous approach fails in reaching the point, due to overshoots generated by the controller. Not taking into account the roll angle, the yaw PID controller becomes unstable, and the ornithopter deviates from the desired trajectory.

However, the new approach based on the simplified model allows the ornithopter to reach the target position. In both three cases, the controller could correct the trajectory. The errors are bigger now, as the space is reduced for the significant changes in the heading. Although the gains may be further optimized to reduce the overshooting and reach the target point with higher accuracy, the robustness of the controller is proven, reaching the final position with a maximum error under 1 m.

The performance of the controller can be observed in fig. 5. Note how the delay of the internal control causes a small overshooting in the outer loop. The gains of the outer loop should be adjusted to have this delay into account in future works.

IV. Conclusions

A new approach for the lateral tracking of ornithopters has been presented. Based on simplified models from pre-

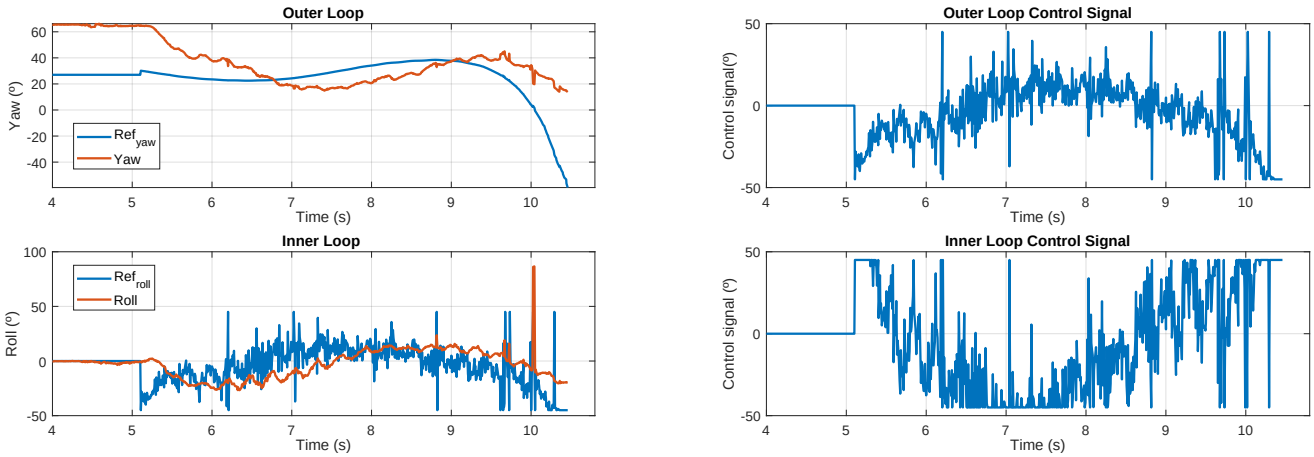

Fig. 5. Internal signals of the lateral controller during flight.

vious works, the dynamics of the FWUAV are analyzed to transform the lateral actuation, given by the deflection of the vertical tail, into a controlled trajectory. This approach was presented in [16] for circular trajectories, but it is modified now for general lateral tracking.

This improved lateral tracking is used here for the case of the perching scenario, with a significant reduction of the error in the perching position. Even though the previous approach was precise enough to guarantee the perching in the most favorable scenario, the reduction of the trust interval opens the possibilities for manipulation tasks once perched, where the precision in the arrival point is key.

However, the new approach proves to be useful not only for the perching maneuver in a favorable scenario. Experiments carried out varying the initial conditions show how the FWUAV is capable of tracking the target point in a wide range of cases, where the previous approach failed. A further adjustment of the gains may lead to a higher accuracy in the tracking. However, as the FWUAV needs to fly forward to maintain flight, not having hovering capabilities, there are also limitations for the maneuvers in reduced spaces.

Results showed here are a first step for the use of ornithopters in different tasks. Improved lateral precision in the perching maneuvers allows the FWUAV to perform manipulation and inspection tasks once perched. Furthermore, lateral tracking can also be used to develop a complete ornithopter-based autopilot, able to track waypoints in flight and perform flight tasks autonomously with high precision.

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