Avian-Inspired Grasping for Quadrotor MAVs

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***Abstract*—Micro Aerial Vehicles (MAVs) have been used in a wide range of applications [9, 7]. However, there are few papers addressing high-speed grasping and transportation of payloads using MAVs. We are interested in dynamic acquisition of targets using MAVs. Drawing inspiration from aerial hunting by birds of prey, we designed and equiped a quadrotor MAV with an actuated appendage which enabled grasping and object retrieval at high speeds. We developed a nonlinear dynamic model of the system, demonstrated that the system is differentially flat, planned dynamic trajectories using the flatness property, and presented experimental results with pick-up velocities at 2 m/s (6 body lengths / second) and 3 m/s (9 body lengths / second).**

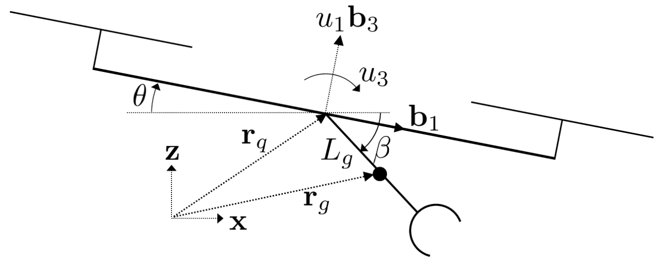

Fig. 1. The quadrotor has control inputs u_1 in the $\mathbf{b}_3$ direction and u_3 as a moment about the axis into the page ($\mathbf{b}_2$). The gripper forms the angle β with the horizontal and its center of mass is located a distance L_g away from the quadrotor's center of mass.

I. Introduction

Predatory birds have the ability to swiftly swoop down from great heights and grasp prey from the ground, water, and air while flying at high speeds. Although recent years have seen improvement in the capabilities of Micro Aerial Vehicles (MAVs) [6], such dynamic aerial manipulation, common in nature, has not been achieved using MAVs.

Video analysis of birds of prey, such as the bald eagle (*Haliaeetus leucocephalus*) shown in Fig. 2, reveal that an eagle sweeps its legs and claws backwards during its capture phase, thereby reducing the relative velocity between the claws of the predator and the prey [3]. This allows the bird, without slowing down, to have a near-zero relative velocity of the claw while grasping the prey.

II. Design of an Articulated Gripper

We use an underactuated three-fingered gripper design which allows the claw to conform to the target while being driven by a single servo motor.

To reduce the relative speed between the gripper and the target, we use the strategy employed by the eagle, which sweeps its legs backward during grasping. In particular, the gripper is mounted on a rotating arm, which is actuated by a servo motor. When the arm rotates, the gripper swings backwards which reduces the relative velocity between itself and the payload during acquisition.

III. Dynamic Model

We define x_q and z_q as the x and z positions of the quadrotor, β as the angle of the gripper arm with respect to the horizontal, and θ as the pitch of the quadrotor. The control inputs are the total thrust (u_1), the moment resulting from differential thrust (u_3), and the torque from the servo at the "hip" (τ). Then, the dynamics of the robot can be modeled using an Euler-Lagrange approach,

$$\mathbf{q} = \begin{bmatrix} x_q \\ z_q \\ \theta \\ \beta \end{bmatrix}, \text{ and } \mathbf{F} = \begin{bmatrix} u_1 \sin(\theta) \\ u_1 \cos(\theta) \\ u_3 - \tau \\ \tau \end{bmatrix}$$

so that

$$\ddot{\mathbf{q}} = D^{-1}\left(\mathbf{F} - C\dot{\mathbf{q}} - G\right) \tag{1}$$

where the matrices D, C, and G are all non-zero. Note that, because of the gripper, $C \neq 0$.

IV. Differential Flatness

The coupled system comprising of the quadrotor and the actuated gripper, whose dynamics is given by (1), is differentially flat with a set of flat outputs given by

$$\mathbf{y} = \begin{bmatrix} x_q & z_q & \beta \end{bmatrix}^T, \tag{2}$$

Consequently, any sufficiently smooth trajectory in the flat output space is guaranteed to be dynamically feasible for the coupled system. Further, nondimensionalized kinematic analysis of an eagles motion provides boundary conditions for the motion planner.

V. Results

We demonstrate experimental results on an Asctec Hummingbird quadrotor [1] equipped with a gripper. The experiments utilize the GRASP Multiple Micro UAV Testbed [8] and leverage a motion capture system to estimate the state of the quadrotor [2]. The target is a small cylinder and is tracked using VICON [2].

With this setup, the quadrotor grasped the target while moving at 2 m/s with a success rate of 100% out of 5 attempts. Additionally, the quadrotor was able to successfully grasp the target while moving at speeds up to 3 m/s, or 9 body lengths / second (Fig. 2). For more details, including a video of the experiments, see [10].

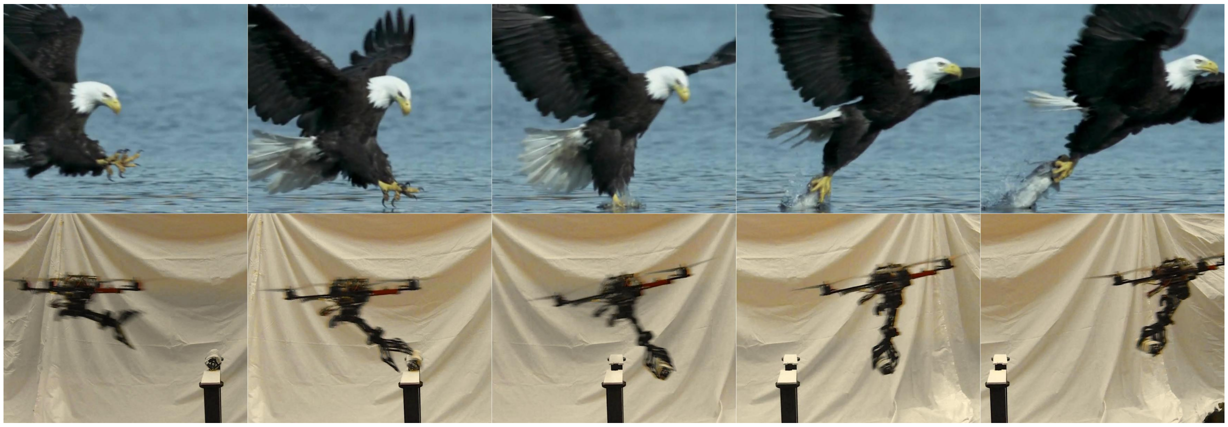

Fig. 2. A still image comparison between the eagle (extracted from [3]) and the quadrotor for a trajectory with the quadrotor moving at 3 m/s (9 body lengths / second) at pickup. See [10] for a video of the grasping.

VI. Current Research

To enable dynamic grasping and perching outdoors, our current research is directed towards developing a visual servoing [4, 5] based control system, which will allow detection of a cylinder that could be used for grasping or for perching on objects such as tree branches or railings.

A diffeomorphism exists between certain image features and trajectories in the flat space. Leveraging this, we can develop a dynamic model and plan dynamically feasible trajectories in the image feature space. In addition, an image-based controller with feedback directly from the image features has been developed. Our system uses a global shutter camera with contour detection of the cylinder running at 60 Hz on a Gumstix. The approach has been verified in simple hover experiments. Finally, combining the controller with the trajectory generation, we will be able to use a single camera in the feedback loop to follow trajectories while tracking or grasping cylindrical objects.

VII. Conclusion

We have explored the challenges of high-speed aerial grasping using a quadrotor MAV equipped with a gripper. A novel appendage design, inspired by the articulation of an eagle's legs and claws, was shown to enable a high rate of success while grasping objects at high velocities. The dynamic model of the quadrotor and gripper system is differentially flat, and minimum snap trajectories were generated for dynamic grasping. Experimental results have been presented for quadrotor velocities of 2 m/s and 3 m/s (6 - 9 body lengths / second).

Current research focuses on the formulation of the presented strategy as a visual servoing problem, which will enable truly autonomous grasping and perching. Towards this, we have developed a vision-based controller and have shown that dynamically feasible trajectories can be planned for the image feature space. Finally, extension to the 3D case by exploiting image moments for estimation of the cylinder's orientation in the image is currently under development.

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