RAPTOR: Rapid Aerial Pickup and Transport of Objects by Robots

Aurel X. Appius†∗, Erik Bauer†∗, Marc Blöchlinger†∗, Aashi Kalra†∗, Robin Oberson†∗, Arman Raayatsanati†∗, Pascal Strauch†∗, Sarath Suresh†∗, Marco von Salis†∗, and Robert K. Katzschmann†

Abstract—Rapid aerial grasping through robots can lead to many applications that utilize fast and dynamic picking and placing of objects. Rigid grippers traditionally used in aerial manipulators require high precision and specific object geometries for successful grasping. We propose RAPTOR, a quadcopter platform combined with a custom Fin Ray® gripper to enable more flexible grasping of objects with different geometries, leveraging the properties of soft materials to increase the contact surface between the gripper and the objects. To reduce the communication latency, we present a new lightweight middleware solution based on Fast DDS (Data Distribution Service) as an alternative to ROS (Robot Operating System). We show that RAPTOR achieves an average of 83% grasping efficacy in a real-world setting for four different object geometries while moving at an average velocity of 1 m/s during grasping. In a high-velocity setting, RAPTOR supports up to four times the payload compared to previous works. Our results highlight the potential of aerial drones in automated warehouses and other manipulation applications where speed, swiftness, and robustness are essential while operating in hard-to-reach places.

I. INTRODUCTION

Dynamic aerial grasping [1] is a recent research challenge that bears much potential to enable many new applications in automation and hard to reach places. Advances in soft robotic grippers, namely the increased tolerance for tracking errors and additional damping when picking up objects, allow for grasping at higher speeds with mobile platforms such as multicopters. Multicopters and soft robotic grippers are a natural match for aerial manipulation as they are easy to maneuver and provide much versatility as a research platform. These properties have been beneficial for quadcopters in a wide range of applications such as point-to-point deliveries [2] and aerial manipulation [3]. While there is extensive previous work on normal flights, recent approaches continue to incorporate new features of quadcopter platforms [1], [4], [5].

We continue to push the boundaries of dynamic aerial grasping with RAPTOR—a flying robot consisting of a soft robotic gripper attached to a quadcopter. Our approach utilizes the maneuverability of the quadcopter platform while the soft gripper ensures robustness and adaptability to the object geometry and size. The resulting system is capable of grasping a variety of objects up to a total maximum payload of 400 g. In addition, the quadcopter reaches average grasping velocities of up to $1 \text{ m/s}$ and velocities of up to $6 \text{ m/s}$ when not carrying a payload.

A. Related Work

Combining robotic grippers with flying platforms opens a new dimension for aerial object transfer. Thomas et al. [6] have demonstrated the feasibility of this approach by picking up cylindrical objects with a quadcopter using an attached swing arm. Recent work shows the potential of using nonlinear model predictive control for a quadcopter in the context of aerial manipulation [7]. Moreover, related work explores high speed deliveries using a hook for high speed delivery [8] and high speed grasping with passive rigid claws [9]. The challenge of increasing robustness towards unknown object geometries and surfaces can be addressed with soft robotic grippers. Soft robotics [10], [11] has been a growing field of research, with many biologically inspired soft tendons and grippers being developed [12], [13], [14]. In particular, the discovery of the Fin Ray® effect [15] opens up many possibilities for the application of soft grippers. In addition, related work shows that tilting the ribs [16] and combining hard and soft materials [17] enhances gripping strength and proposes tendon-driven robot hands for high speed grasping [18]. Fishman et al. [1], [19] propose a tendon-driven aerial gripper mounted on a quadcopter. This approach uses adaptive control methods to compensate for the unmodeled aerodynamics such as a ground effect that induces tracking errors. In their experiments, they report a 91.7% success rate over a sample size of 23 grasping
attempts with a grasping speed of $0.2 \text{ m s}^{-1}$. Our goal is to address some of the open challenges, particularly with regard to the robustness to object geometry and grasping at high velocities.

### B. Contribution

In this paper, we propose a platform for aerial grasping with a significantly increased performance compared to previous works in rapid aerial grasping. We present an exhaustive description of the system architecture, including a novel approach to middleware using a custom Fast DDS (Data Distribution Service) wrapper as well as the electromechanical design of the drone platform and the gripper. Our Fast DDS wrapper is significantly faster compared to ROS (Robot Operating System) while being lightweight and cross-platform compatible.

In addition, we demonstrate the effectiveness of our system through real-world experiments that showcase high grasping speeds and robustness to different object geometries. Our platform shows significant improvements over previous works for rapid aerial grasping with RAPTOR and outlines the future research challenges for aerial manipulation.

### C. Outline

Section II provides an overview of the system architecture with particular emphasis on the integration of the different subsystems. This is followed by a motivation of the mechanical design decisions in Section III, describing the custom components we designed and manufactured as well as the modifications we made to off-the-shelf components. In Section IV, we explore our trajectory generation and control strategies for robust trajectory tracking. Finally, we illustrate our results in Section V and show an exhaustive experimental validation of our platform and conclude the paper in Section VI with an outlook into future work.

## II. SYSTEM ARCHITECTURE

### A. System Components

For subsystems like the drone, there already exist off-the-shelf components that allow us to compose our systems in a way to only develop custom components where needed. This allows us to maximize our efforts towards developing a robust system for grasping. We divide our system into three logical subsystems: 1) the drone, 2) the gripper module mounted on the drone, and 3) offboard components.

1) **Drone Components:**
- Raspberry Pi 4B (Companion computer)
- Pixhawk 4 (Flight controller)
- XBee Pro Zigbee Module (RF communication directly to PX4 flight controller)

2) **Gripper Components:**
- Arduino Nano (Microcontroller for gripper control)
- Hobbywing BEC 3A (Step down LiPo voltage from 14.8V to 6V for servos)
- Two Megmoki MG995 Hi-Speed Servos (Gripper actuation)

3) **Offboard Components:**
- 19 Vicon MX-40 cameras (Motion capture data)
- Laptops/PCs (Trajectory generation and logging)

### B. Middleware Design

Robotic systems often use ROS [20] as middleware, as it provides an easy to use API and several bundled tools that are commonly used in robotics including for simulation, visualization, and mapping. However, the ROS1 transport system does not satisfy the temporal deadlines and fault tolerances required for real-time systems. This requirement is especially relevant for safety-critical systems like flying robots and autonomous vehicles. In addition, ROS1 is not a suitable choice for embedded systems due to its resource-intensive nature.

ROS2 addresses these issues by replacing the transport system with Fast DDS, an open-source industry standard for real-time communication. Fast DDS has proven successful in safety-critical applications such as aerospace, smart grids, defense, financial trading, and power plants. Underneath, it is a fully distributed system of high-performance point-to-point connections, avoiding data bottlenecks and single points of failure. The system continues to run even if individual nodes crash or restart. A key benefit of Fast DDS is that the discovery server handles all detection and configuration automatically when a new node is connected. These features allow the user to focus on transmitting structured data rather than the mechanics of communication.

ROS2 offers an API similar to ROS1, with support for multiple programming languages including C++ and Python. This means that messages must undergo format conversion twice: from ROS2 to Fast DDS while sending and from Fast DDS to ROS2 while receiving. Consequently, two internal notifications are required per publishing/subscribing event. This increases the latency by a factor of up to 1.5 [21]. Clearly, ROS2 is not the best choice for time-critical communication channels. On the other hand, native Fast DDS implementations provide the best performance, but they are much more complicated to use. We use a custom, lightweight wrapper over the native Fast DDS implementation that offers an API similar to ROS. To retain the same high-performance characteristics, we use only C++ abstractions and avoid message format conversions. The downside is that other programming languages are not directly supported. Communicating with Python programs is supported via bindings (pybind) at the cost of much higher latency. However, it is not an issue in our case since all time-critical functions are implemented in C++. Moreover, ROS2 is not officially supported on Raspberry Pi OS—the operating system for our onboard computer (Raspberry Pi). Our wrapper retains the cross-platform capability of native DDS implementations: Windows, macOS and most Linux distributions including Raspberry Pi OS are supported out of the box.

1) **Motion Capture System:** An overhead motion capture system tracks the pose of objects in the 3D space and publishes this information to the local network via Fast DDS. Although the system can run at frequencies higher
than 250 Hz, we have found a frequency of 100 Hz to be sufficient.

![Diagram of component architecture of the quadcopter platform]

III. Mechanical Design

We explored different state-of-the-art approaches for the design of the gripper: a pneumatic activation [23], [24], [25] as well as a deformable finger approach (Fin Ray®) [26]. We created and evaluated various prototypes based on the following criteria with the corresponding weights:

- Actuation Time (30%)
- Gripping Force (20%)
- Fabrication (20%)
- Total Weight (20%)
- Adaptability/Robustness (10%)

By assigning weights to the different criteria, we were able to compute a score to evaluate the best approach for our use case. Each criterion was given a score from 1 to 10 and then weighted accordingly, yielding a maximum score of 10 for each approach. Table I shows such a comparison between the Fin Ray® and the pneumatic approach. Since the former outperformed the latter in terms of gripping force and ease of fabrication, we proceeded by developing successive iterations of it as prototypes. We then tested our prototypes using only the essential elements on the drone platform.

Throughout the development of the drone and the gripper, our main focus was on the agility of the quadcopter to allow for actuation and grasping at high velocities. Based on this idea, we built a lightweight version of the components, using the Fused Deposition Modeling (FDM) 3D printing for our prototypes due to its ease of use and speed.

A. Drone Design

We modified the Holybro X500 platform to achieve our objective of a lightweight design. This was done by adding mounts for the items discussed in Section II-A.1. We arranged the placement of the different components such that the center of gravity remained in the middle of the platform while providing easy access to the various units.

The Holybro X500 platform consists of carbon fiber plates and tubings as well as plastic connectors. We 3D printed the mounts for the added components and decided to use PLA as the manufacturing material thanks to its ease of printing and mechanical characteristics, which are sufficient for our use. In particular, the temperatures near the PLA parts do not exceed the critical threshold temperature of 55°C, at which PLA begins to soften.

B. Gripper Design

1) Fingers: The fingers of the gripper are designed to bend via the Fin Ray® Effect [27]—the tip of the structure bends toward the applied force, which enables the fingers to interlock with an object. This additional interlocking mechanism enhances the maximum payload in comparison to a rigid gripper which only works through static friction. Based on previous work on jamming capability [28], we tilted the ribs, further increasing the generated force.

In addition, we modified the original shape of the Fin Ray® from an equilateral triangle to a right-angled triangle, which allows for two parallel faces once the gripper is closed. This enlarged contact area enhances the gripping security.

2) Actuation and Control: For actuation, we use two MG995 servo motors. They are controlled by an Arduino Nano, which receives the angle settings for the servos from the Raspberry Pi 4B. The rotational movement of the gripper is guided on one side by the servo and the other side with a bearing. There is a component that connects the bearing and the rotor in a bow shape to allow for the rotational movement to happen. On each bow, there are two fingers at a distance of 25 mm attached to the bow part. The fingers are in parallel so that they align with their counterpart. There are two servos and therefore two bows and four fingers.

3) Mount: We mounted the gripper construction on the drone via two parallel tubes that are fixed due to friction with a rubber piece. The counterpart of the gripper has two holes to accommodate the tubes. Further, there are two rectangular holes in the mount for the servos. The servos can be fixed to the mount using four screws. Additionally, one part of the bearing of the bow from Section III-B.2 is also a part of the mount. Figure 4 illustrates the complete gripper assembly as

![Diagram of complete gripper assembly]
Onboard estimation and control

Offboard planning

Mocap estimates

Delay

Flight trajectory generator

Flight controller

Gripper controller

User commands

Global Planner

Vehicle dynamics

Fig. 3. Dataflow architecture of the quadcopter platform. We use a global planner while the minimal-jerk trajectories are computed using the trajectory generator by Mueller et al. [22]. The default controller implementation of the PX4 flight controller handles the onboard estimation and control with slightly adjusted PID parameters that are omitted here. All controls are acting based on the pose given by the motion capture system, whereas the delay is accounted for in the PX4’s state estimator.

Fig. 4. The last iterations of the gripper fingers. We tested each iteration in a custom-made testbed until we arrived at a gripper iteration with sufficiently compliant fingers to bend around objects and fully utilize the compliant aspect of a soft gripper. The gripper is mounted below the drone.

allows for the compensation of small latencies by a user-configurable parameter. We use the low-level attitude and attitude rate controllers that are available by default on the PX4. The attitude controller is a nonlinear PD controller and runs at 500 Hz. The attitude rate controller is a tightly tuned PID controller running at 1000 Hz.

2) Offboard Control: Our system architecture allows us to run computationally heavy tasks in real time on offboard computers with more computational power. The motion capture data published on the local network can be accessed by the offboard computers through Fast DDS. Using the pose of the drone and a target object, waypoints are computed in real time at a frequency of 50 Hz. These high-level commands are then sent directly to the PX4 over an additional XBee wireless radio link. Additional applications for logging, plotting, and simple high-level commands are also run on offboard computers to allow for the rapid testing of new software and hardware components. These applications are able to communicate via Fast DDS using either shared memory if run on the same computer or the User Datagram Protocol (UDP) if run on different computers.

3) Gripper Control: Attached to the bottom of the drone is a gripper module consisting of two arms actuated by a high-speed servomotor each, which are in turn controlled by an Arduino Nano microcontroller. Any high-level commands sent by the offboard controls through the local network via Fast DDS are first received by the Raspberry Pi before being forwarded to the microcontroller using the UART serial communication protocol.

V. Experiments

A. Setup

We tested RAPTOR with four different objects: 1) an irregularly shaped styrofoam object, 2) a small planar cardboard box, 3) a paper roll, and 4) a 0.5 L PET bottle.
Figure 5 shows the different object geometries used in our experiments with the drone and the gripper and Table II highlights the different dimensions and masses associated with each object. We placed these objects on a custom-made stand made out of aluminum profiles. The stand ensured that object positioning remained consistent both throughout and during the attempts. For each object, we performed a total of 36 grasps. We performed all grasping attempts over two consecutive days with the same gripper as seen in Figure 4. Between these attempts, we only landed the drone to exchange the battery to ensure that the condition of the drone remained the same.

**B. Results**

Table III shows the success rates and average velocity as well as the standard deviation for successful grasping throughout the swooping motion to pick up the object for the 36 swooping motions per object. We define each swooping motion to begin at a distance of 2 meters away from the object and end 2 meters behind the object. Based on these assumptions, we computed the average speed with the time needed to complete the full motion and the distance traveled. We can observe that for all the object geometries tested, the average grasping velocity is approximately 1 m s⁻¹.

Figure 7 and Figure 8 illustrate the trajectories and velocities of the drone during pick-up attempts respectively. Moreover, they show the amount of vertical travel required to lift an object from the stand. The styrofoam object requires the least vertical travel to be lifted from the stand while the other objects require a larger vertical travel of approximately 4 cm. As we are not modelling this effect in our control scheme, if the drone gets stuck in the swooping motion trying to lift up an object, this can both reduce the momentary velocity of the drone and cause an overshoot following a successful grasping of the object from the stand.

In addition, we notice a very reliable grasping performance for the styrofoam object and the box, with the drone consistently able to pick up the object while moving at an average speed that is five times the speed reported in previous works for an actively controlled gripper [1]. Performance degrades as we transition to smaller objects such as the paper roll and the PET bottle due to reference tracking noise in the xy-plane. There is a clear correlation between the width of the object and the grasping success of RAPTOR, which can be seen with rigid grippers as well [9]. Notably, the other dimensions of the object do not seem to have an impact on success. This demonstrates the advantages of compliant soft grippers. They are largely invariant to the surface smoothness of the object that is to be grasped—the styrofoam object has the roughest surface while the box has a very smooth surface. Even when the quadcopter only achieves a partial grasp with two fingers, it maintains a steady grip with no noticeable degradation in trajectory tracking. Additionally, based on our results, we can expand previous works to smaller objects and achieve higher grasping efficacy for our two largest objects [1].

**C. Limitations**

1) **Failure Modes:** We also observe that the failures are primarily due to the controller of the quadcopter not tracking the reference accurately enough in the xy-plane and missing...
the object by flying past it without making contact. Whenever it achieved a sufficient reference tracking such that at least two fingers made contact with the object, the quadcopter could complete a successful grasp. Objects did not slip out of the gripper once they had been grasped, even if the grasp was only with one pair of fingers. This behavior could be observed across all objects with their respective surfaces and shapes. Grasp mistiming is also not an issue, since the gripper is actuated only if the drone is in the close vicinity of the object that is being grasped.

2) Reference Tracking: Figure 10 shows the plots for the planar coordinates of the drone in more detail. Here, the deviation for the grasping attempts for each object is clearly visible. Given that the width of the gripper is approximately 6 cm and in most cases, we only need to have contact with one of the two pairs of fingers for a successful grasp, this allows for a deviation that should be approximately half of the width of the object. Considering Table II and the width of the objects, a deviation of only a few centimeters towards one side of the objects will already have a major effect on grasping efficacy, particularly for the objects with the smallest width.

3) Ground Effect: Moreover, near the ground, aerodynamic effects such as the ground effect [29] add additional factors of uncertainty to the drone dynamics which the controller does not account for. Previous works have attempted to model the ground effect [30] and even account for it with a controller [1], but there have been no controllers proposed to counter the effect for the dynamic grasping of objects. Recent learning-based approaches [31] have been shown to reduce tracking uncertainty, but they are currently unable to generalize to different environments.

VI. CONCLUSION

With RAPTOR, we demonstrate a platform for robust dynamic aerial grasping. Using soft grippers, we can successfully grasp objects of different geometries and surface finishes, even at high speeds where traditional rigid grippers would fail. We describe our system architecture and mechanical design in detail, drawing comparisons between our custom system components such as our custom Fast DDS wrapper and existing solutions for building similar robotic systems as well as motivating our design decisions, particularly for the soft gripper. We then evaluate our system using real-world experiments that validate our design decisions and show significant improvements compared to previous works. In particular, we were able to show robust grasping at high speeds—with average velocities of 1 m s\(^{-1}\)—while our quadcopter could also grasp smaller objects that have additional requirements for reference tracking, showing potential for a wider range of applications.

While there are many frontiers in dynamic aerial grasping that require further research, we see the more precise modeling of aerodynamic ground effects for reference tracking as the main challenge to consistently picking up small objects, especially when the drone is operating close to surfaces. Moreover, future work will require to address the challenges associated with making the platform independent of motion capture systems while exploring the picking up of objects without a stand due to the additional force caused by the propeller thrust. An accurate and computationally feasible model of aerodynamic effects will therefore be a major milestone for a more robust dynamic aerial grasping.

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Fig. 9. Grasping sequence for our quadcopter platform. The drone approaches with the gripper open and as soon as the drone has reached the target position, the gripper closes, lifting up the object.

Fig. 10. The y-coordinate (lateral translation with respect to the object) of the drone during the pick-up attempts of the different objects. The trajectory varies significantly during different attempts. The approach of the object is consistently distributed across approximately 10 cm.

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