UAV for Sticking Markers in the Built Environement

Wen-Shuo Hsu[1], Soroush Fazeli[1], Kepa Iturralde[1,2], Christoph Holst[1]

[1]Chair of Engineering Geodesy, School of Engineering and Design Technical University of Munich, Germany
[2]Chair of Digital Transformation in Construction, Institute of Construction Management,
Faculty of Civil and Environmental Engineering, University of Stuttgart, 70569 Stuttgart, Germany.

wenshuo.hsu@tum.de, soroush.fazeli@tum.de kepa.iturralde@br2.ar.tum.de christoph.holst@tum.de

Abstract -

UAVs have immense potential in construction applications. This paper gives a overview of a project that aims to expand the frontier of applications of UAVs from non-contact measurements to physically interact with buildings by sticking targets on the building. The goal of the project is to apply positioning tags onto a facade of an existing building with UAV. This paper looks into hardware, software and simulation aspects of the UAV and elaborates on advantages of the chosen solutions. Moreover, the UAV has been tested in laboratory environment.

Keywords -

UAV; Automation; ROS; Simulation; built environment

1 Introduction

Unmanned Aerial Vehicles (UAVs) are becoming popular as a solution to automation of a wide variety of tasks in different fields. For construction application, [1] utilized UAV to facilitate contact test for bridge inspection with a 1-DOF manipulator. [2] applied UAV for sensor installation and retrievement. [3] gives a thorough review on UAV with active multiple DOF manipulator and its development throughout the years.

The goal of this project is to apply AprilTags, a type of visual tag that provides localization with high accuracy and low overhead, onto facades of buildings with an automated UAV. These accurate positioning tags can later be used as reference for installation of insulated prefabricated modules with solar energy systems. UAVs are lightweight and low-cost, therefore it can be deployed fast and with multiple units simultaneously.

A quadcopter with an end effector was developed. The quadcopter will approach the target position with AprilTags loaded on the end effector. On the back side of the tags is adhesive applied. Once the tags have made contact with the target surface, the quadcopter will apply pressure on the tags to ensure a firm binding. The process is indicated in Fig. 1.

Compared to [1] and [2], our end effector does not require its own DOF. AprilTags are released mechanically. The contact position, force, angle is manipulated through controlling the vehicle directly. This reduced complexity and lighten its weight.

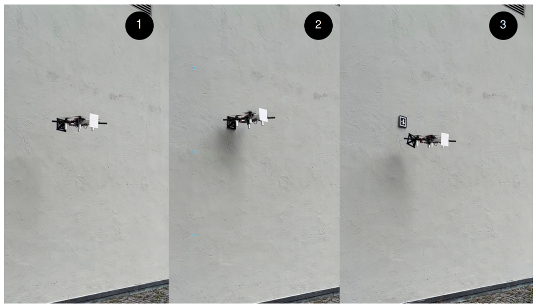

Figure 1. Sticking Process, check the video

2 Design

As an experimental platform, the controllability, payload capacity and adjustability of dimension are the three priorities. Adjustability enables the UAV to operate with a wide variety of propellers for different payloads. X-shape quadcopter is chosen because of its symmetric maneuverability and controllability on X-Y plane.

Although multicopters with more motors have higher payload capacity than a quadcopter, the end effector would not have enough space between evenly spread motors. Stacking two motors vertically was also examined. However, in light of the efficiency loss of the second propeller [4], the additional thrust gain cannot compensate for the excessive complexity.

The size of the quadcopter, the diagonal shaft-to shaft distance between motors, is designed to be adjustable from 238 to 650 mm to be compatible with propellers up to 15 inches. This assures the quadcopter to be compatible with a heavy end effector. Compared to [5], the battery is moved from bottom to top. This brings 2 advantages. First, the battery is located closer to the Center of Mass (COM). As one of the heaviest parts on an UAV, moving the battery closer to the COM results in a smaller moment of inertia, which enhances the quadcopter's agility. Second, the battery on the top is more accessible for operators. Operators can install a battery much easier. It is also more feasible to develop an automated battery exchange process with a battery on the top in the future.

The flight controller is located between upper and lower plate of the quadcopter. This change minimized the distance from COM to onboard Inertial Measurement Unit (IMU) to 23 mm, which can minimize the extra centripetal acceleration an IMU experienced when turning around COM and hence increase its accuracy.

3 Hardware

Hardware choices were made with max compatibility in mind. Within the budget limits, the power system is designed for a drone weighing 2.5kg.

Table 1. Hardware Overview

Motor	T-Motor F100 2820 1100KV
Propeller	HQ8037-3
Battery	6s 2200mAh
Flight controller	Raspberry pi 4B w/ Emild Navio 2
Electronic speed controller (ESC)	T-Motor F55A PRO II
RC receiver	FrSky X8R
Laser range finder	GY-53
IMU	LSM9DS1

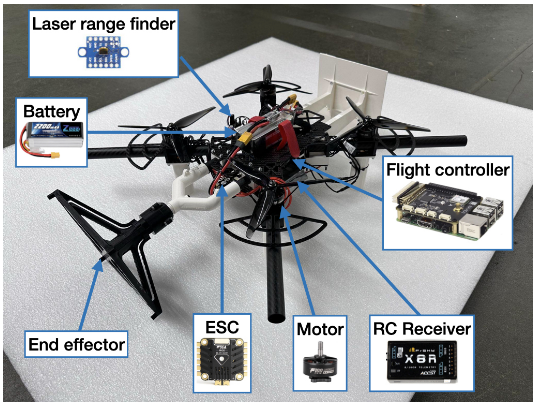

Figure 2. Hardware Position

Although propellers with higher pitch can generate more thrust, these propellers are also prone to being caught into Vortex Ring State (VRS), which results in lose of lift and control [6]. The adopted 8037 propellers have smaller pitch than the manufacturer's recommendation.

Although high kV motors on the old model [5] can generate more thrust with the same size, more current is drawn from batteries and more waste heat is generated. This results in less overall efficiency, which leads to a shorter flight time. By contrast, a low kV motor with high voltage has less side effects while having same output. Therefore, compared to previously 2550kV, the new motors' kV value is selected as 1100kV.

Low kV motors require higher voltage to operate. Thus, a 6-cell battery (rated at 22.2V) is used.

4 Material and Manufacture Process

For manufacturing, CNC machined Carbon Fiber Reinforced Polymers (CFRP) and Fused Deposition Modeling (FDM) with Polylactic Acid Plastic (PLA) are widely used.

CFRP is widely used in the aerospace industry because of its strength and stiffness with low density. In the case of this project, CFRP is used in critical parts such as arms which are cantilever beams with motors on the open end. The stiffness of beams can suppress vibration induced by motors and propellers. The main piece of the frame is also consists of CFRP, where this stiff material acts as a high pass filter against vibration, which is crucial to the precision of the vibration-sensitive onboard IMU.

FDM can shorten the time of manufacturing. Also, it can create sophisticated infill pattern inside work piece, which can be optimized and achieve high specific strength. Parts such as landing gears and brackets for sensors and controllers, which do not experience high shear stress, are made out of PLA with FDM.

5 End Effector

AprilTags is fixed in a square frame. After the end effector makes contact with the surface, the square frame will be pushed back by the surface and releases the AprilTag. At the end of the sticking process, the quadcopter is given the command to move forward to apply pressure on the AprilTag for a firm binding. In order to move forward, a quadcopter pitches downward. To compensate the pitch angle, a ball joint is added as shown in Fig. 3.

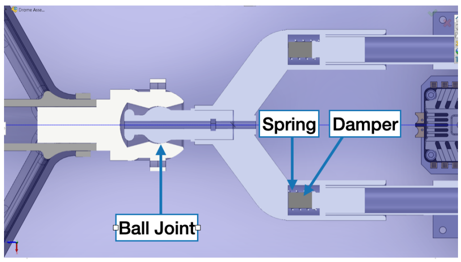

Figure 3. Cutaway View of End Effector

The ball joint can also absorb some misalignment of the quadcopter w.r.t. the target surface. To allow soft contact with surfaces, the end effector can slide along the rods stemming from the main frame. Springs and dampers between two parts can reduce the reaction force from the surface pushing the quadcopter away.

6 Simulation

To affix the tag to the wall, the drone must make contact, subjecting it to external forces that can introduce disturbances and nonlinear dynamics. Addressing this challenge involves measuring and integrating these forces into the system. This integration enables the controller to compensate for the forces, ensuring stability during flight and minimizing the impact of disturbances. One method to measure these forces is by incorporating force sensors on the drone. These sensors can gauge the forces during interaction, providing feedback to the controller. By assessing changes in the drone's attitude, the controller can adjust propeller speeds to maintain flight stability and ensure sufficient force is applied to affix the AprilTags to the wall. However, it's worth noting that this approach may be costly due to the price of force sensors and the additional weight they introduce, potentially impacting the drone's motors and battery requirements. Due to this drawback of using sensors, these forces can be measured in simulation. Hence the task of the drone can be tested in the simulation to assure a stable flight during the interaction and evaluate the performance of the controller. With the simulation, the drone would have certainly lower cost and probable crashes could be prevented. However, in the robotic industry majority of the simulations are implemented in well-known simulations like Gazebo or other ones which will not provide force measurements. Unity [7], a popular game engine, facilitates the simulation of drones by employing a physics engine to model dynamic behavior and measure applied forces. Objects, including the asymmetric drone, are treated as rigid bodies within Unity. To ensure accurate simulation, Solidworks models of the drone are utilized. Unity's robust rendering capabilities extend to testing computer vision algorithms, such as detecting a drone equipped with an AprilTag. The high rendering ability of Unity is crucial for accurate position estimation by the ground camera in detecting the drone and other tags on the building.

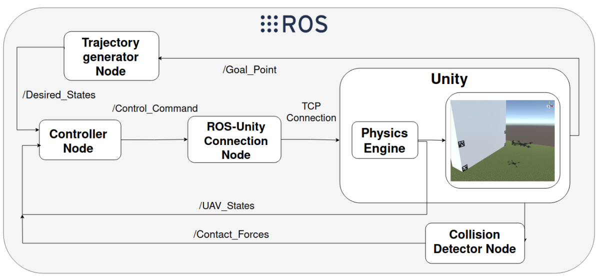

Figure 4. Simulation Diagram

On the other side what makes unity a perfect tool for us is that it can be easily integrated with ROS. Robot Operating System (ROS) [8] is an open-source robotics middle ware suite. ROS optimizes communication in robotics through hardware abstraction, low-level device control, common functionality implementation, and inter-process message passing for diverse computer clusters. Unity's simulation can seamlessly integrate with the controller and other components of the software stack via ROS, enabling effective communication between them. In the ROS network illustrated in Fig. 4, the ground camera within Unity detects tags and transmits desired waypoints. This information guides the trajectory generator to produce and publish desired states for the controller.

6.1 Controller Design

The controller node is a key part of the software stack, utilizing a geometric controller inspired by [9]. It processes desired states, computes errors in the drone's state space, and works to mitigate these errors for enhanced control. The control of the transnational dynamics of a UAV involves the management of the total thrust, denoted as $-fRe_3$. The magnitude of the total thrust, represented by f, is under direct control, while the direction of the total thrust, denoted as $-Re_3$, aligns along the third body-fixed axis b_3.

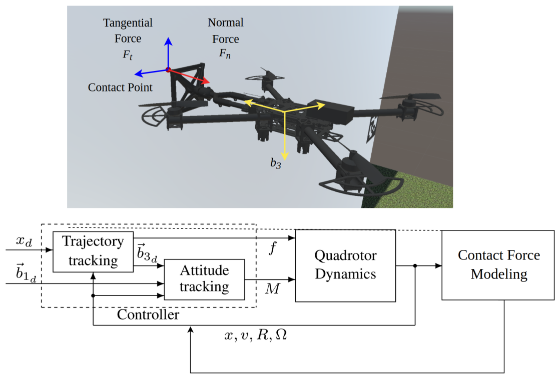

Figure 5. Controller Structure

The UAV's interaction with the wall provides feedback for the controller to make informed decisions on velocity, ensuring stability and precise tag placement. The contact force applied on the drone will be in two direction, The contact force applied on the drone will be in two directions, one is tangential, and the other one is perpendicular to the moving direction. The drone needs to adjust its velocity and orientation in order to assure an approach normal to the wall. Thus the forces applied on the drone from the interaction would be minimized.

7 Results

The aerial system, controlled via a remote controller, combines autonomous algorithms to achieve precise and dynamic maneuvers. The inclusion of sensors such as an Inertial Measurement Unit (IMU) ensures stable flight by providing real-time data on the drone's orientation. The integration of a laser range finder enhances the manipulator's spatial awareness, allowing it to accurately gauge distances from the walls. The drone was initially tested in a simulation environment to evaluate the controller's performance and accuracy. Subsequent testing on the physical drone assessed the controller's performance on hardware. The following section delves into the obtained results and overall performance.

7.1 Simulation

In simulation tests, the drone controller's performance was assessed based on its stability during wall interactions and accuracy in placing the target. Key metrics included contact force, drone velocity, stability, and target placement, measured by considering the collision area and the number of contact points. Results are summarized in the table below:

Table 2. Simulation Results

Case	Contact Force (N)	Velocity (m/s)	Accuracy (m)
1	2.9	1	0.01
2	7.7	2.4	0.05
3	12	4.8	0.11

7.2 Experimental Setup

In the experiments, the Ardupilot flight controller and geometric controller played key roles in drone operations based on RC commands and real-time sensor data. The Ardupilot ensured the drone's stable flight, while the geometric controller significantly improved maneuvering precision. To address differences between simulation and real-world experiments, the Extended Kalman Filter (EKF) was employed for state estimation, effectively managing uncertainties, especially in state determination using data from the IMU and laser range finder. Despite arguments surrounding certain factors, the comparison struggled to precisely evaluate the controllers' adaptability in real-world scenarios. However, the drone successfully completed its tasks, showcasing practical functionality despite the inherent difficulties in accurately comparing simulations with real experiments.

8 Conclusion

In conclusion, the project successfully demonstrated the quadrotor's ability to interact with and attach a target to a wall in both simulation and real-world tests, showcasing practical applications like surveillance and object manipulation. The integration of robust control mechanisms showed promise, and insights gained from improved simulation contact force modeling suggest potential for refining the system. Future developments could benefit from a better controller design, informed by insights gained through enhanced simulation, to further optimize the performance and adaptability of versatile quadrotor systems.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No.958445.

References

[1] I. Takahiro et al. Wall contact by octo-rotor UAV with one dof manipulator for bridge inspection. In *2017 IEEE/RSJ IROS*, pages 5122–5127, 2017. doi:10.1109/iros.2017.8206398.

[2] H. Salua et al. Sensor installation and retrieval operations using an unmanned aerial manipulator. *IEEE RA-L*, 4:2793–2800, 2019. doi:10.1109/lra.2019.2918448.

[3] A. Ollero et al. Past, present, and future of aerial robotic manipulators. *IEEE T-RO*, 38:626–645, 2021. doi:10.1109/tro.2021.3084395.

[4] M. Ramasamy. Hover performance measurements toward understanding aerodynamic interference in coaxial, tandem, and tilt rotors. *Journal of the AHS*, 60(3): 1–17, 2015. doi:10.4050/jahs.60.032005.

[5] K. Iturralde et al. UAV for target placement in buildings for retrofitting purposes. In *Proceedings of ISARC*, volume 40, pages 593–596. IAARC Publications, 2023. doi:10.22260/isarc2023/0080.

[6] W. Johnson. Model for vortex ring state influence on rotorcraft flight dynamics. Technical report, 2005.

[7] A. Juliani et al. Unity: A general platform for intelligent agents. *ArXiv*, abs/1809.02627, 2018.

[8] M. Quigley et al. ROS: An open-source robot operating system. In *Workshops at the IEEE ICRA*, 2009.

[9] T. Lee et al. Geometric tracking control of a quadrotor UAV on se(3). In *49th IEEE CDC*, pages 5420–5425, 2010. doi:10.1109/cdc.2010.5717652.