# 6-DOF UAVs for RPO Simulation

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## ABSTRACT

Rendezvous and proximity operations (RPO) started early on in humans' journey to space. This has allowed for satellites and spacecraft to dock with each other, and for us to build amazing machines. Among the things possible from this concept are the International Space Station and Hubble Telescope. The manning and upkeep of both rely on RPO to be completed consistently. Additionally, RPO is becoming increasingly useful in the military and private space sectors. However, hardware testing for close proximity trajectories can often be cost prohibitive. Using a 6 degree of freedom (DOF) unmanned aerial vehicle (UAV) to simulate spacecraft missions and test payloads helps alleviate testing costs and accelerate development. These UAVs, called omnicopters, can move in any direction at any arbitrary orientation. This allows for more accurate simulation of on-orbit conditions without being in space. These machines are relatively cheap to build and operate, costing no more than commercially available UAVs. This could not only help reduce the upfront research and development costs but also help increase the number of payloads that get to orbit. We have assembled the frame and components needed for the operation of the omnicopter but have not been able to get the software to operate as intended.

## 1. INTRODUCTION

John F. Kennedy's famous "We Chose to go to the Moon" speech helped kick off a space race that eventually put humans on the moon. To achieve this feat, NASA had a lot to learn about space operations and what was truly possible. This resulted in a handful of years long programs and many manned space launches. They tested the physiological effects of space on humans, extravehicular activity, or space walks, and, in the late stages of the Gemini program, the ability of two spacecraft to meet up and dock while orbiting our planet.[6] The demonstration of RPO had implications that reached far beyond getting to the moon.

In the 1960's, space travel was a wildly expensive endeavor. Everything had to be built from the ground up, and lessons about how to operate in space cost both money and lives. Today, space is frequented by both countries and companies, although this is primarily with unmanned operations. In recent years, the cost of a space launch has been reduced considerably through the advent of reusable booster rockets. However, getting to space is still expensive at about $1,500/kg to low earth orbit being the cheapest.[7] The cost of launch falls on top of the development of the spacecraft and their payloads themselves. Extensive testing is needed to ensure smooth operation of these payloads when they finally reach their destination in orbit. To accomplish this, both software and hardware simulations are carried out. Software simulation has relatively low barrier to entry and is quite cost effective as the computing power needed is easily accessible. However, hardware-in-the-loop testing remains an expensive and specialized undertaking. There are various forms of hardware testing that each have their own advantages and disadvantages. Air bearing platforms are commonly used but require a dedicated workspace and cannot actuate all six degrees of freedom.[8]

Ideally, the most accurate testing of hardware would be done in space itself. This would allow for the full 6-DOF behavior necessary to test a system in its entirety. However, in most cases this is not feasible due to the cost and dangers of failure. The various forms of RPO simulation help address the different kinds of tests needed to verify the performance of these spacecraft and their payloads.[2] Kinematic simulations deal with an external actuator implementing the translational and rotational characteristics of the spacecraft flight. Dynamic simulators rely on isolating the platform and use actuators that are representative of what the actual spacecraft uses.[5] These can also be combined into hybrid systems that allow for varied aspects of the spacecraft and payload to be tested. Other platforms are available, such as specialized aircraft operating in a parabolic flight path which helps simulate the microgravity/freefall environment. These aircraft are expensive to operate and only a few examples exist.

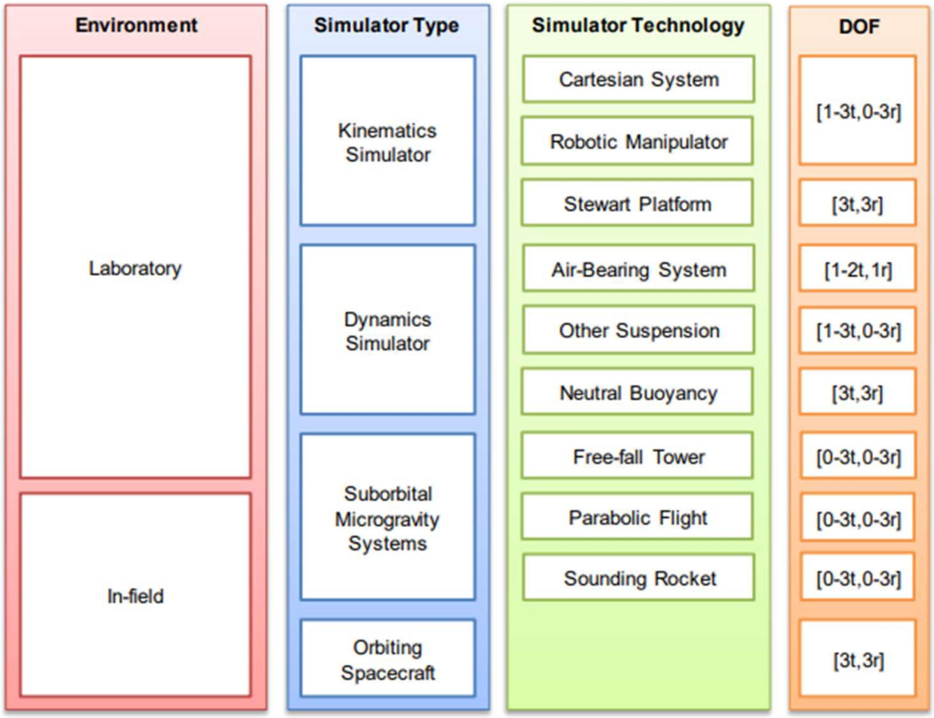


**Figure 1**. RPO Simulation Types[5]

The addition of a 6-DOF UAV, dubbed an omnicopter, could help with hardware testing. A drone that has command over the 6 degrees of freedom – 3 degrees of attitude and 3 degrees of position – is a relatively new concept with a handful of proven designs.[1][2] This opens a new avenue of hardware testing and simulation and helps address many problems that arise with the other testing methods. These drones are much more portable, cost-effective, and accessible than the dedicated testing facilities located at a handful of locations throughout the world. Additionally, multiple drones are able to be flown at the same time. This allows for multi-vehicle, 6-DOF, hardware simulations to be conducted. This has the potential to be a huge breakthrough for RPO simulation and component design. Before, almost all hardware simulations involved a singular moving vehicle.[5] Which is adequate for testing a singular payload, but testing multiple payloads designed to work in conjunction with each other is a more complicated endeavor.

## 2. METHODOLOGY

### 2.1 Design inspiration

While there are various 6-DOF UAV designs available, this project attempts to replicate the design of Brescianini and D'Andrea.[1] This design was chosen due to the availability of instruction on the build process as well as its demonstrated ability to operate with a payload. A few modifications were made for our specific design constraints, however due to the off-the-shelf nature of the build, there should not be any issue with using different parts. The open cube design and use of 8 props give it better lifting ability and modularity when compared to other designs that have been made. Examples of both can be seen in the figure below.

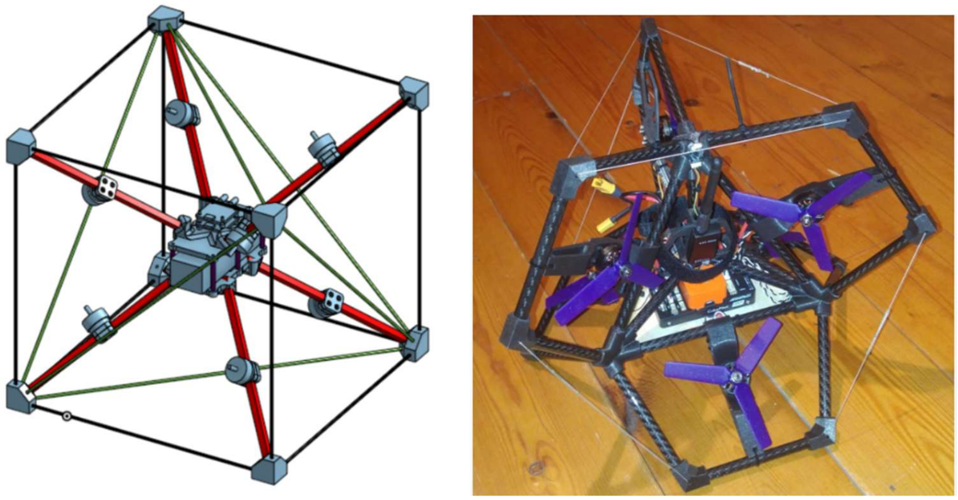

**Figure 2.** 6-DOF UAV designs[1]

The Brescianini and D'Andrea design can be seen on the left whereas the design on the right is from Peter Hall. Both utilize carbon fiber frames with 3D printed parts. However, the Brescianini and D'Andrea design is larger with the previously mentioned central area that could be payload capable. Hall's design makes for a good 6-DOF demonstrator, but its utility outside of that scope is small. The control laws of the two designs are also significantly different due to the difference in the number of props.[1][4]

### 2.2 Starting the Build

Our build was guided by the PX4 write up that replicates the Brescianini and D'Andrea design. Included in this are complete 3D models of the system as well as STL files of all 3D printed parts. Below is the parts list.

| Omnicopter Bill of Materials | |
|---|---|
| **Electronics** | |
| Flight Controller | Notes |
| PixHawk 2 | Flight controller. Must have capability to support 8 motors |
| | |
| ESC | |
| Tekko32 F4 | 4-in-1 electronic speed controllers. (x2) |
| **Propulsion** | |
| Motors | |
| Brother Hobby LPD 2306.5 | Price for 8 motors |
| Gemfan Propeller | price for 8 propellers |
| Battery | 6s 3300mAh. Check dimensions to ensure it will fit in the frame. |
| Battery strap | |
| **Frame** | |
| Carbon square tube | 8x7x1000 mm/.314x.236x39.4 in (x2) |
| Carbon rods | 3x2x1000 mm/ .118x.079x39.4 in (x8) |
| Screws | M3 x 12mm (x40); M3x35mm (x4) |

**Figure 3.** Omnicopter Parts List

The omnicopter utilizes 3D printed middle section plates, frame corners, and motor mounts. The middle section and the frame corners were printed with PLA and the motor mounts were printed with ABS. The carbon composite pieces that make up the frame were cut using a handheld rotary tool with a cutoff wheel. The eight, 8mm square tubes that the motors are mounted on are 240mm in length. The 3mm diameter rods that make up the exterior frame measure 328mm in length.

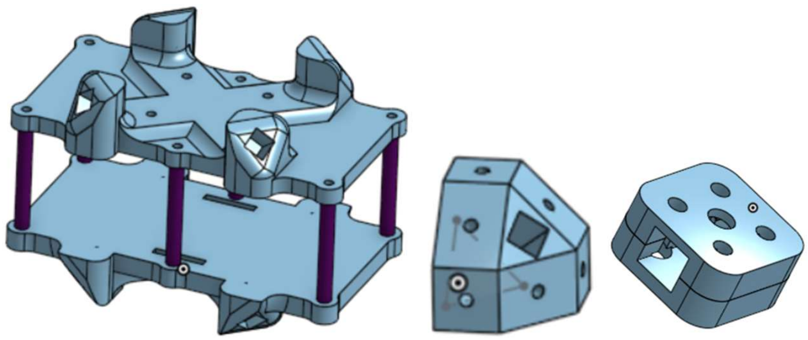

**Figure 4.** 3D Printed Assembly Parts

The motors were mounted using the 3D printed fitting shown on the right side of Figure 4. This simply clamps onto the square carbon tube with four screws. They were mounted as far away from the center as possible without the props breaking the plane of the exterior frame. It is important to mount the motors so their relative orientations are correct. Failure to do so would result in difficulty controlling the vehicle and potentially make it impossible to operate in 6 degrees of freedom.

The battery chosen was a 6s 3300mAh unit. This is mounted in the middle of the frame and held in place by the pressure from the top and bottom plates. Multiple manufacturers make this type of battery, but their dimensions can vary. It is important to verify that the battery will fit prior to purchase.

The electronic speed controllers (ESCs) were mounted on the top part of the middle section using 4 through bolts with the supplied vibration dampers. Two, 4-in-1 ESCs were used as a compact solution to power the 8 different motors. A battery connector was soldered onto the controllers, and a custom wiring harness was made to connect the ESCs to the motors.

A Pixhawk 2.1 auto pilot was used with a mini carrier board. This deviates from the original design and was used to satisfy the U.S. government purchasing requirements. The use of this part is suitable for the build, however there are lighter options available if purchasing requirements are not present. The Pixhawk was mounted on the bottom of the middle section using Velcro strips and further secured using a strip of tape. The default forward orientation of the Pixhawk was placed in such a way that the number 1 motor is in the most positive octant of the vehicle. A custom wiring harness was made to connect the ESCs to the auto pilot.

**Figure 5.** Omnicopter with ESCs and Autopilot Mounted

After mounting the auto pilot, a telemetry link was added. While there are many options for telemetry links, we tried to use the lightest solution we had on hand. The telemetry range and power requirements for this application are negligible. This telemetry link allows for the ground station to connect wirelessly to the auto pilot. This can be used to set up parameters for the operation of the omnicopter, as well as set up missions and flight paths.

These are the basic components needed for operation. Our design chose to use a Vicon chamber to give the autopilot positioning data in lieu of actual GPS connectivity. This decreases the weight of our design but also limits it to indoor operation. If outdoor operation is desired, a GPS antenna would be needed for the autopilot to get positioning data.

Programming the correct settings for the omnicopter is a difficult endeavor as there is not default omnicopter setting. Our build opted to use the QGroundControl ground station and run the PX4 firmware on the autopilot. For the airframe setup, a generic multi-rotor airframe much be chosen, and the motor positions need to be set up in a three-dimensional space instead of a coplanar setup found in most traditional multi-rotor aircraft.

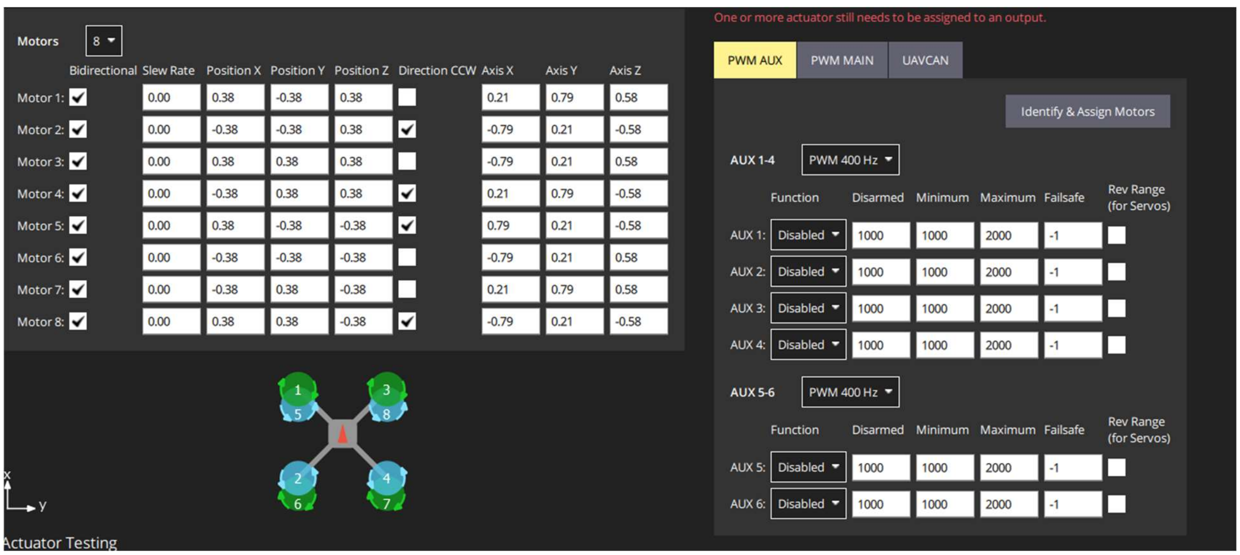


**Figure 6.** Omnicopter airframe setup

Using the indicated positive axis on the software, the known positive position of the autopilot, and the motor numbering scheme from the ESC data sheet, the location and orientations of the motors was able to be programmed. The positions are measured in feet from the center of the omnicopter. The orientation axes are normalized and based on where the motor shafts are pointing in relation to the positive axis of the omnicopter.

## 3. RESULTS

The omnicopter hardware has been assembled, however, it has not gotten off the ground yet. Our suspicion is that a failsafe is being triggered in the software that is preventing the system from operating. Our current troubleshooting hasn't provided additional insight onto what the exact solution to this problem is.

## 4. CONCLUSIONS AND FUTURE WORK

The omnicopter is an ongoing design challenge. We hope to achieve the maiden flight soon and demonstrate the ability to manipulate the 6 degrees of freedom made possible with this design. After the flight characteristics have been figured out, we hope to add a payload. This could be an actuator or a sensor that could be used for testing. We also hope to make more examples and run multiple vehicle missions to simulate an on-orbit RPO.

## 5. REFERENCES


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