# Prototype vs. Pandemic: Initial Testing of Autonomous Aerial Robots for Sanitizing Large Open Spaces with UV-C Light

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## The Problem

Hospitals have been testing and deploying semi-autonomous ground-based robots to sanitize patient rooms and testing booths to keep staff safe to deal with the rapid influx of COVID-19 patients. While there are chemical sanitizers cleaning staff can use, one of the most promising areas of recent development is the use of LED UV-C light as a sanitizing agent. For example, Danish-based UVD Robots market a semi-autonomous ground-based robot that can sanitize an entire hospital room in ~10 minutes.

This application works well for a ground-based robot designed to navigate buildings like hospitals or office spaces, but scaling up to large spaces like airports, sports arenas or convention centers prove to be an almost insurmountable challenge. An aerial robot would be able to more easily navigate complex environments, cover a larger area, and allow human operators to stand out of harm's way.

We've seen some successful deployments recently by EagleHawk with aerial drones that spray disinfectants into the air. This is a valid approach, but it comes with a set of unique challenges:

- The disinfecting agent can potentially corrupt or degrade flight components and hinder the operability of the robot.
- Disinfectants also have the potential to corrupt hospital equipment and HVAC systems if not cleared by the EPA
- There's no proper verification if the area was sanitized
- Semi-autonomous aerial robots still require a line-of-site operator to monitor the vehicle, as well as staff to handle any spraying equipment

Knowing these limitations and needs, our team at Exyn started to explore the potential of UV-C light mounted to an aerial robot as a sanitizing agent. UV-C has been proven to disrupt the virus RNA after exposure for a set amount of time. But the following questions arose:

- Could a UV-C light (or similar) on an autonomous aerial robot be an effective and efficient way to sanitize public spaces, sports arenas, and other high-contact areas in order to protect us from diseases and viruses like the coronavirus?
- How much surface area can we sanitize in a given period of time?
- What are the limitations of this application?

With a potential sanitizing agent identified, the team quickly began the process of designing, testing, and prototyping a sanitizing platform that could be used autonomously in large spaces. You'll see below how our hardware team created a custom LED payload and had it performing test flights in a matter of weeks.

## Background Information

- UV-C light has been demonstrated as an effective method of sanitizing air, surfaces, and liquids
- UV-C light disrupts DNA/RNA structures and leads to the inactivation of bacteria, viruses, and protozoa
- Peak wavelength for UV-C sanitizing is ~260-280nm
- Exposure time for a surface is dependent upon total irradiation, measured in mW/m^2
- Given payload constraints, UV-C LEDs offer a possible opportunity for a drone-based sanitizing solution

## Operational Requirements

### Safety

- The robot should do no harm. While there's a good chance this robot will only be operating in empty buildings, it should be able to detect and avoid humans and other obstacles. It would require the human operator to be outside the building or affected area at all times.
- UV-C light can be harmful to humans. It is recommended to avoid eye and skin contact. Therefore the drone should be able to be operated beyond line-of-sight or at an adequate standoff distance.

### Sanitization

- The robot will require sanitization before and after each use. Along with identifying areas in need of sanitization, the robot must navigate to and hover over the affected area for the proper exposure time.

### Verification

- The robot must be able to communicate to the mission controller which areas have been properly sanitized.

### Efficiency

- The robot should be able to properly sanitize an affected area within the flight time constraints of the robot and without becoming an undue burden on society.

## Our Approach

1. Research potential UV-C LED modules to be mounted on the robot

2. Identify vendors and partners, existing development or engineering kits

    a. Exyn engineers identified an engineering development module within the Klaran Light Engine product line from Crystal IS. The 9 LED Light Engine engineering module features 9 high-performance UV-C LEDs that emit UV light in the target germicidal range (260-270nm). The product is designed for surface and air sanitizing applications and was readily available to evaluate our drone-based implementation.

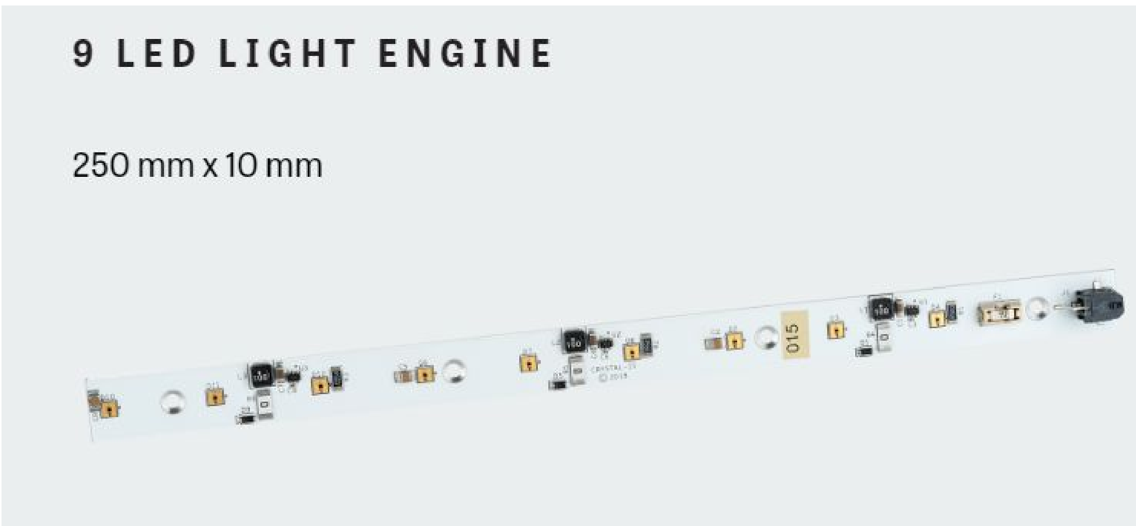


Fig. 1: UV-C LED light array (Klaran Light Engine) used for proof-of-concept testing.

    b. Consulting with the Crystal IS application engineers, we were able to simulate performance of the UV-C LED light engine at a standoff distance of 1 meter. At a 1 meter distance covering a .5x.5 meter area, the intensity of a single strip ranges from .015 to .025 mW/cm$^2$. Under those parameters, a 90-99% reduction of E.Coli in ~1.5 minutes was expected. Note that exposure time may vary depending upon the target pathogen. Specifically, longer exposure time is necessary to eliminate viral pathogens, like the coronavirus, versus bacterial. In order to maximize germicidal capacity and minimize the exposure time, we designed our test payload to feature 4 of the 9 LED light engines, for a total of 36 UV-C LEDs in our implementation.

    c. According to the Klaran 9 LED light engine datasheet, and confirmed by in-lab testing, the module draws roughly 2A at 12V, or 24W. Available power on the drone platform is around 50W, so to support the 4 LED modules, we designed the payload to integrate a secondary battery power supply. An additional advantage to this approach is that the UV-C payload may be operated independently of the drone platform and exynAI software, while also easily swapped between vehicles. The power supply, a 14.4V, 7500 mAh custom LiPo battery pack, is able to support ~50 minutes run time for the 4 LED strip payload.

3. Collect performance metrics - power draw, time to sanitize, standoff distance

    a. A key factor in the ability to sanitize a given surface is the offset of the UV-C payload from the surface. The closer we can get to a surface, the higher incident radiation power, the greater the germicidal effect, and the less time required to hover in place. However, in developing our tests, we tried to strike a balance between standoff distance, coverage area, and time to sanitize. Based on simulated results and ground testing, we set a target standoff distance of .5 - 1m.

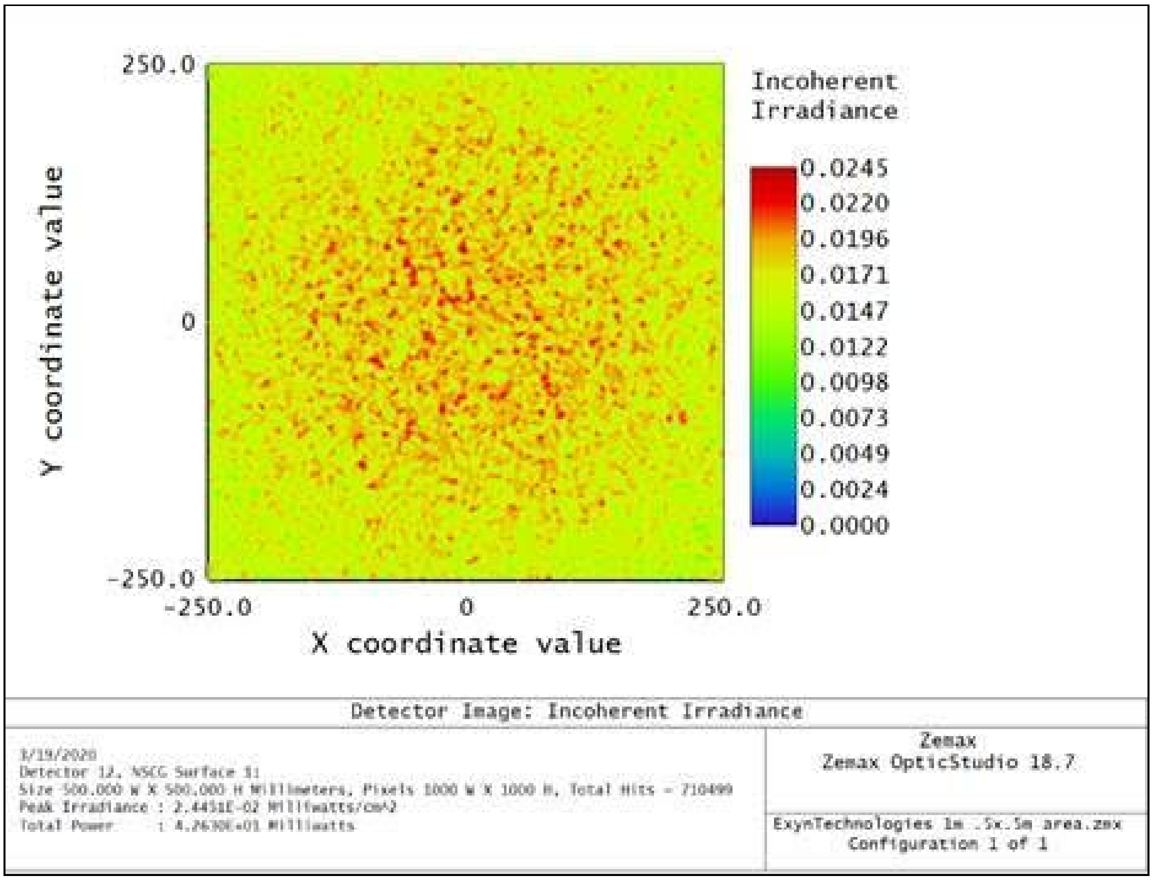


Fig. 2: Simulated irradiance provided by Crystal IS (Distance: 1 m, Target area: .25 sq. m, 9 LEDs)

4. Build LED panel and mounting bracket

    a. The Exyn team designed a test harness to incorporate 4 of the LED light engine strips for a total of 36 LEDs. We leveraged 3D printing to quickly turn around prototypes within a week. For the drone platform, we were able to quickly modify an exynAI powered DJI M210 drone that we have developed for underground survey applications within the commercial mining industry. We repurposed an existing payload harness that the team had developed for defense and government projects and designed the UV-C payload to fit these existing mounting features.

b. Safety rocker switches with LED indicators were included to allow the operator to activate the UV-C LED only when needed. The payload features an integrated 14.4V, 7500 mAh LiPo battery pack, which allows the UV-C payload to be operated independently from the main drone power supply, avoiding significant reduction in the available flight time.

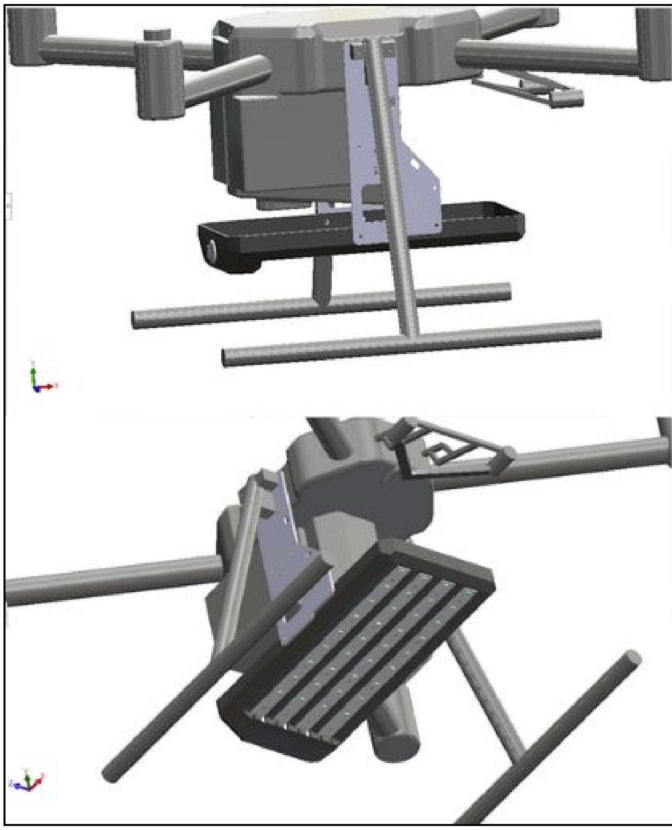

Fig. 3: Digital 3D Models of the Payload

Fig. 4: 3D-printed LED module mounting for flight tests

5. Demonstrate effective sanitization on a live autonomous drone platform

## Testing the UV-C LED Modules

Using the simulated data as a starting point, Exyn Engineers conducted a series of tests to assess the power draw, exposure time, and offset distance for effective sanitization. These outputs are important inputs to the flight planning process. The power draw will give us an estimate of how many LED light modules we can use, while the time to sanitize will provide an estimate of how long is required to hover in place as well as coverage area for a single mission.

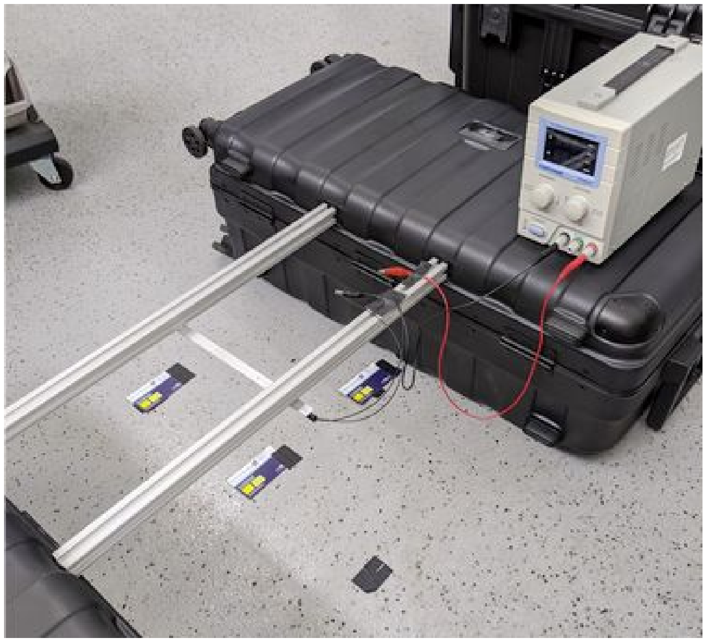

Fig. 5: Testing Apparatus and Setup

**UV-C Indicator Strips**

To measure the germicidal effect of the UVC modules, we utilized UV-C disinfection visualizer strips from CureUV. These strips indicate germicidal irradiation by changing color from yellow to green based on the level of exposure to UV-C radiation. These strips allowed for a qualitative assessment of the germicidal effect.


Fig. 6: Control, no exposure.

**Test Setup**

Before launching any flight tests, we conducted a series of static ground tests to evaluate LED module performance and better understand UV-C coverage area, standoff distance, and exposure times. We mounted the LED light engine strip at a fixed location (Z) above an array of UV-C Indicator Strips with the following layout, measured in meters:

- 1 placed at center (0,0)
- 1 placed at +X (.25m, 0)
- 1 placed at -Y (0, -.25m)

Test strips were exposed at 30s increments at heights ranging from .25m to .5m. At each interval, strips evaluated qualitatively for color change toward green.


Fig. 7: Test Strip Positions

**Test Conclusions**

From these tests, we were able to characterize the time to sanitize a coverage area of .25 sq. m. based upon the standoff distance and number of LED modules used. Our metric for time to sanitize is a perceptible change from yellow to green on the sanitizing strips.

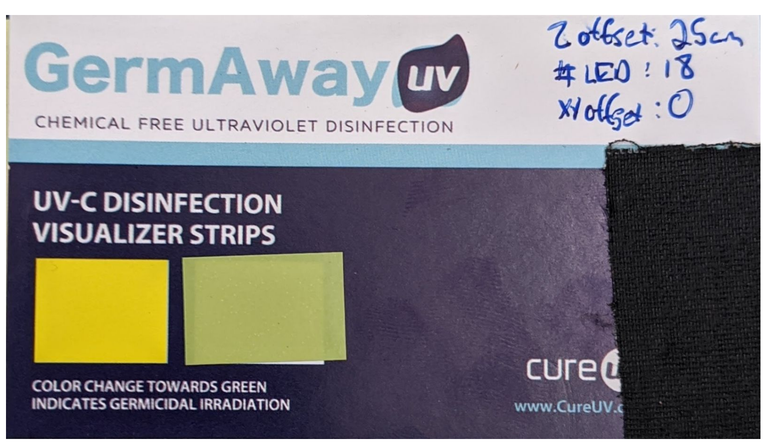


Fig. 8: Test Strip Indicating Effective Sanitization

- 1 LED Strip @ .25 m: approx. 2 min
- 1 LED Strip @ .5 m: approx. 4 min
- 2 LED Strip @ .25 m: approx. 1 min
- 2 LED Strip @ .5 m: approx. 2.5 min

*At least perceptible sanitizing effect as indicated by UVC exposure strips

We found that a single LED light engine strip demonstrates an effective sanitizing effect over the .25 sq. m coverage area in 2 minutes at a .25m offset and 4 minutes at a .5m offset. Doubling the number of LEDs cut the required exposure time nearly in half to approximately 1 minute exposure at .25m and 2.5 minutes at .5m

These static ground tests gave us insights into the relationship between the number of LEDs, exposure time, and standoff height. For safety considerations, we decided to maintain a standoff distance of 1 meter for a live flight test of the UV-C payload. To accommodate for the larger standoff distance and maximize the germicidal effect, while minimizing the hover time, 4 LED light engine strips, for a total of 36 UV-C LEDs, were selected for the prototype UV-C payload. Based upon the ground test data, we predicted this would allow for demonstration of a germicidal effect with 1 minute of hover time on target at a 1 meter standoff height.

## Flight Tests

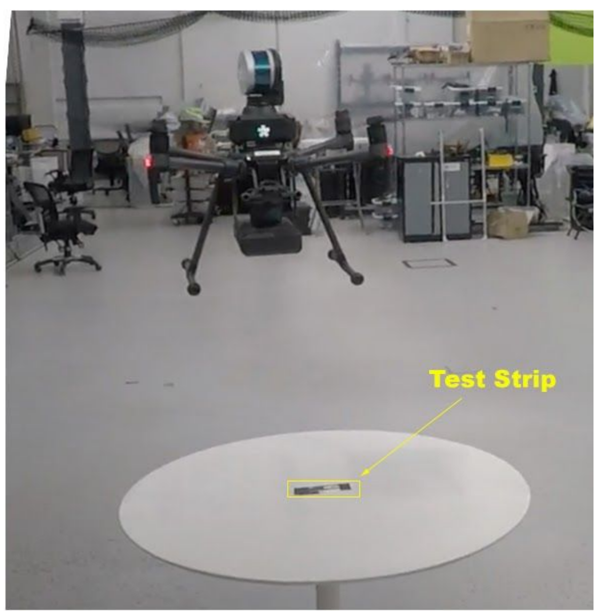


Fig. 9: Test flight in the Exyn offices, test strip secured to the tabletop

- With the LED payload built and tested, it was mounted to the bottom of our A3R Flight Platform for flight tests.

- UV-C testing strips were placed on flat tabletop surfaces at two locations in our office

- Our engineers then created a mission for the robot to fly to each location and hover 1 meter away for 1 minute before returning to it's starting location
- Engineers maintained a safe distance with protective glasses while the robot executed it's mission autonomously
- Testing strips were examined and photographed to assess the sanitizing effect after each flight

Flight Test Video

**Mission Planning**

In order to support the UV-C sanitizing missions, upgrades could be made to Exyn's exView mission planning interface. These changes would allow an operator to identify a location or area to be sanitized from a safe standoff distance. The software would transmit the mission to the robot, which would autonomously plan and execute the sanitizing mission. Meanwhile, the user would be able to monitor the mission from the tablet, including visualizing the flight path and receive status updates on the sanitizing progress. These status updates could be overlaid on the high-resolution 3D map of the environment that the robot generates while in flight.

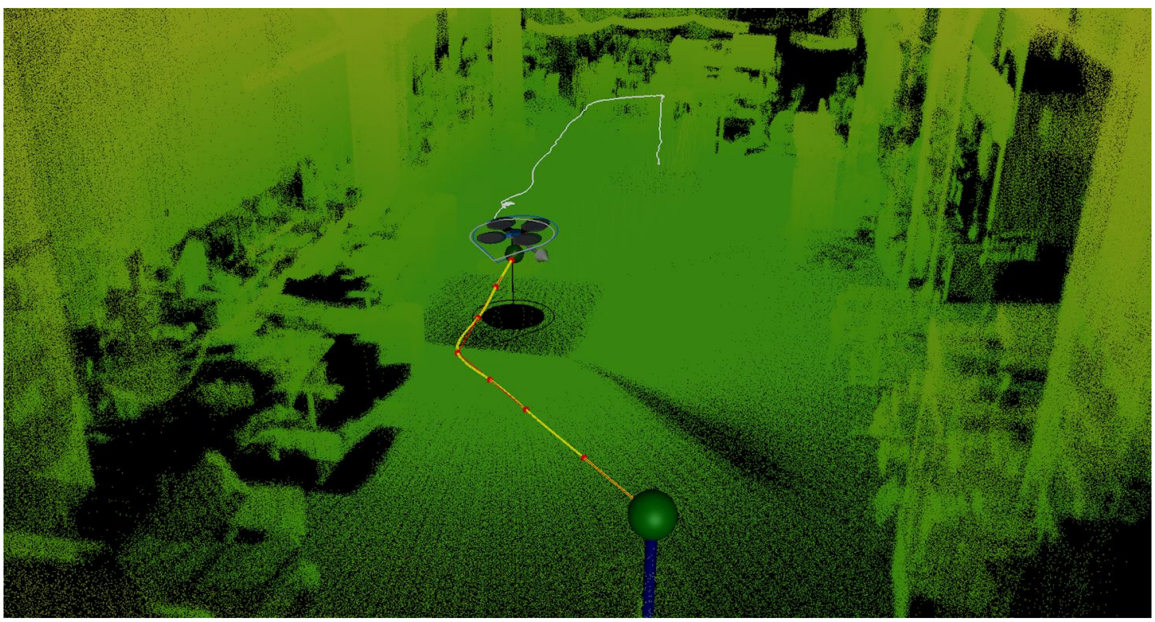

Fig. 10: Screenshots of the exView interface during mission execution. Shown here is the robot as it autonomously plans it's flight path to the second waypoint, indicated by the green sphere.

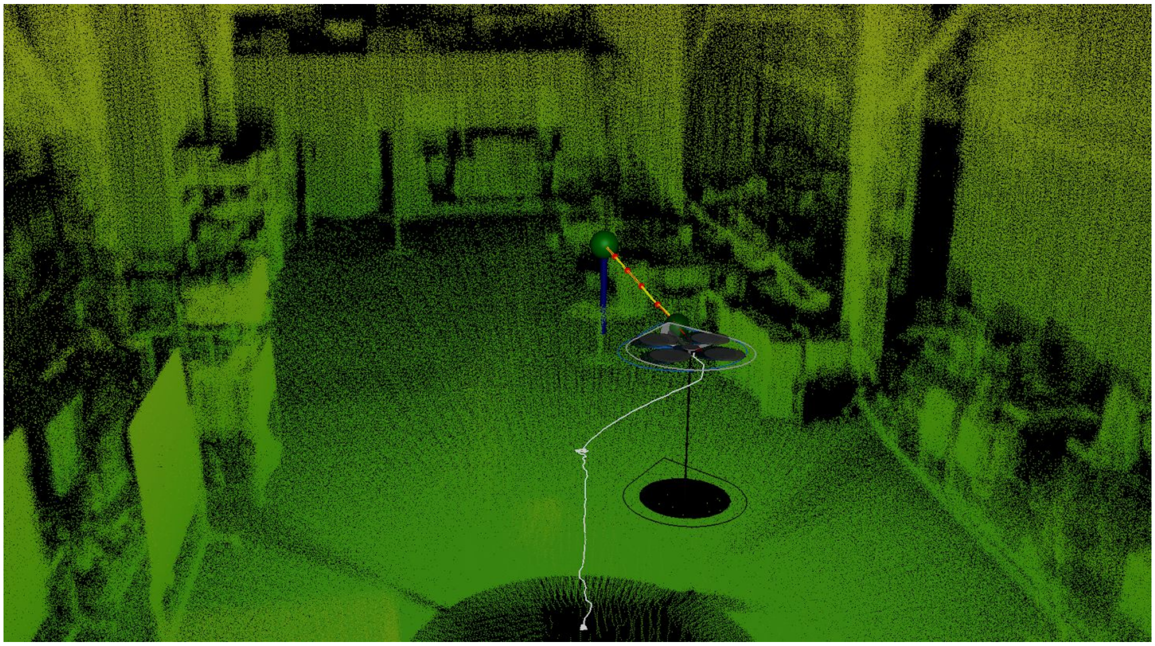

Fig. 11: The exView interface shows the 3D point cloud map as it is built in real-time. The white trail shows the actual path flown by the robot from takeoff to the first waypoint.

**Irradiated UV-C Test Strips Post Flight**


Fig. 12: UV-C test strips from each waypoint indicating successful sanitization.

## Conclusions

The team was successful in quickly researching potential solutions to a world-wide issue and developing a tangible application within a matter of weeks, demonstrating a perceptible germicidal effect with 1 minute of hover time on target at a 1 meter standoff height.

After careful testing, the team concluded that while aerial robots are capable of hovering over and sanitizing a .25 square meter space, the time and power required to ensure mission completion would not be an efficient solution to sanitize large areas at this time.

To be an effective solution for large areas, further advancement is needed in the underlying UV-C LED technology so that effective sanitization could be achieved on the order of seconds rather than minutes.

Higher irradiation intensity over a larger coverage area is needed to sanitize large surfaces at a distance and the power draw would be too large for conventional aerial robots.

The UV-C payload may be more suitable for ground robotics applications, like UVD Robot's drone for hospital rooms, or fixed installations, like a luggage carousel or packaging line.

## References & Resources


- UV-C Testing Kit: https://www.cureuv.com/products/uvc-visualizer-kit
- Crystal IS -- UV-C LEDs: http://www.cisuvc.com/products
- https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3292282/
- https://www.klaran.com/how-a-uvc-led-works
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- https://en.wikipedia.org/wiki/Ultraviolet_germicidal_irradiation
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