Window Cleaning Drone Technical Details

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Abstract

This document explains the technical details of various elements of the window-cleaning project. It includes calculations needed in the beginning to provide estimates that explain how the system works and its limits. This file is intended to supplement and amend the diagram explaining the communications between the drone, remote, and rover.

Electricity

There are 6 motors in our hexacopter, each with an input of 198W and 30A, combining for a total of 1188W and 180A. A standard power outlet in the United States typically transfers about 1800W at 120V 15A. Because the total power is 1800W and the drone takes 1200W, it leaves 600W for the pump, which is more than enough. The electricity from the outlet runs into two separate AC to DC converters with one bucking to voltage down to 12 V to power the pump and one boosting the voltage to 200 V to supply power to the hexacopter. The 200 V current runs through a 14-AWG current up to the drone carrying 1200 Watts or 6 A. On the drone, a DC to DC step-down converter is used to buck the voltage back to 12 V, powering the propeller motors directly. When there is power spared from powering the motors, the leftover power will be utilized to charge the battery. On the other hand, when the power supply cable provides insufficient power for the propeller motors, the battery will supply the leftover power required. This revised design of the electrical system supporting the hexacopter's operation requires more budget allotted for the construction of the sUAS. However, this can be balanced by purchasing less Jet-dry cleaning solution since the indoor testing is expected to be less intensive than the originally planned outdoor testing.

Window Detection System Using Polarizer

Window Detection is an important part of the drone project, and therefore, we devised multiple approaches.

Methods

The possible methods include:

1. Camera with a polarizer
2. Visual recognition of windows
3. Infrared sensor for temperature detection
4. Sensors detecting the acoustic feature of windows

Among the discussed methods above, we decided to use a combination of the first and second methods. Below is a detailed description of our approach to window detection.

Description

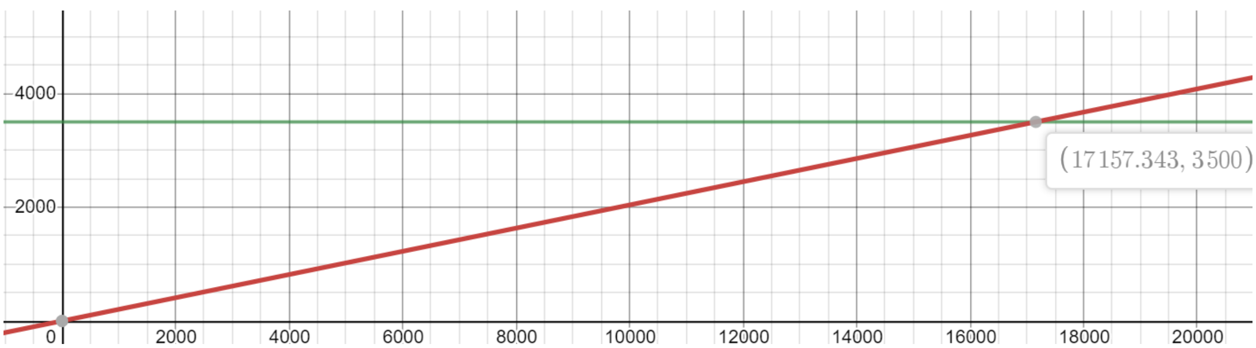
Due to the diamagnetic nature of glass, the sunlight (unpolarized) reflected off the surface of a piece of glass will be polarized partially in some direction. Utilizing this property, a machine learning model can be trained to recognize windows from a camera blocked by a piece polarizer spinning at a specific frequency. To be specific, as the piece of polarizer is spun with certain frequency in front of the camera, the camera will observe a change in the intensity of the light coming in if the light is polarized. Therefore, since the light reflected off a window is polarized, the camera will observe a change in intensity of light in the place where the window is. Then, the trained machine learning model can easily recognize windows by recognizing the changing light intensities.

Length of the Pipe

This section aims to find the relationship between the length of the pipe carrying the water and the mass of that pipe. Two situations are explored: when the pipe is alone, and when the drone is also carrying an electric cable. The main constraint of the length of the pipe when attached to the ground is its mass.

Without Electric Cable

Let the length of our pipe in centimeters be l and the mass of the pipe in grams be M. The inner diameter of our tube is $\frac{7}{64}$in, and the outer diameter is $\frac{3}{16}$in. The density of polyurethane rubber is 1.22 g/cm^3, so the equation for M in terms of l is $M = [(\frac{7}{128} \cdot 2.54)^2\pi + \pi[(\frac{3}{32})^2 - (\frac{7}{128})^2] \cdot 2.54^2 \cdot 1.22]l$. This equation assumes that the density of our solution is 1 g/cm^3, even though that is not exact. We have not yet determined the optimal mixture of water and jet dry, but because the solution will mostly be water, 1 g/cm^3 is our estimate. When M is 3500, l is about 17200 cm. Our drone's payload is around 4kg, so it can handle 3.5kg easily.

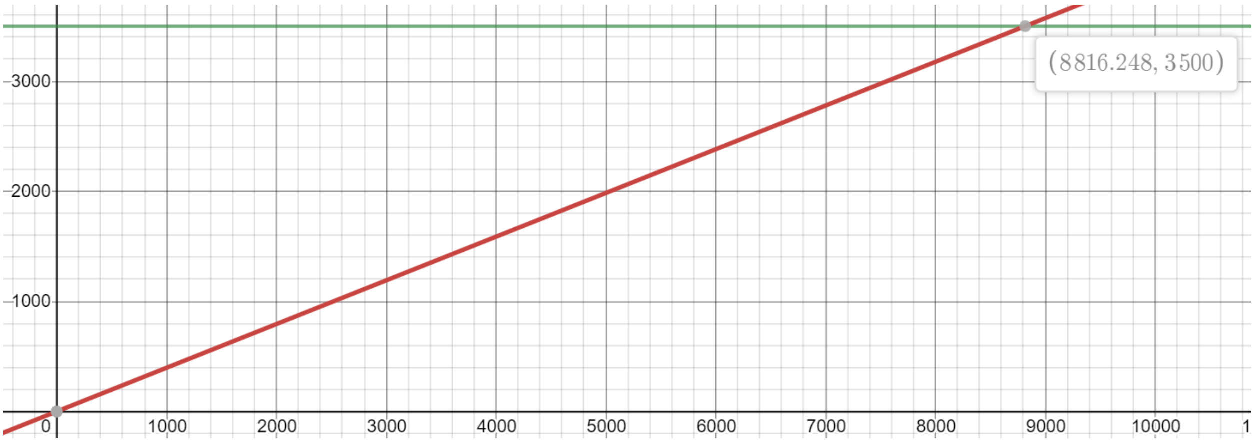


Our graph in desmos

In this scenario, when the pump is on the ground level, the drone will be able to fly up to around 57 stories which is far beyond what is needed, since the drone is only required to reach around 30 stories of height to function in most buildings in the United States and around the world.

With the Electric Cable

Adding on to the previous subsection, we find the mass of the pipe with the electric cable. The weight of the wire is 0.013 lbs/ft, or approximately 0.193 g/cm, we obtain that $M = [(\frac{7}{128} \cdot 2.54)^2\pi + \pi[(\frac{3}{32})^2 - (\frac{7}{128})^2] \cdot 2.54^2 \cdot 1.22 + 0.193]l$. When M is 3500, l is about 8800 cm.

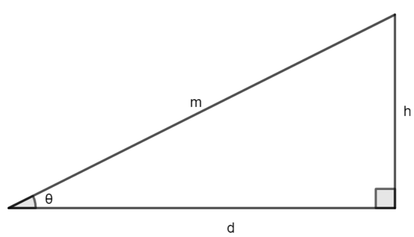


Our graph in desmos

In this case, the drone can reach the height of around 28 floors, which is sufficient for buildings under 79 floors. This is because the pump system of the drone can be placed on top of the building, thus reaching 51 floors downward as well as on the ground level in which case the drone reaches 28 stories upward. The exact reason that pipe system when attached to the top of the building can reach 51 floors downward is discussed in the Sprayer section.

3D Modeling of Environment and Distance Sensing

In the autonomous phase, a LIDAR will be incorporated into the drone for modeling the ambient environment for better flight control and route planning. It will also help the drone avoid obstacles such as buildings. However, the drone is not always perpendicular to the window, meaning there will be calculations to find the distance utilizing the readings of the LIDAR sensor. Let m be the measurement of distance from the LIDAR sensor and θ be the pitch of the drone that the gyroscope gives. We wish to find d, the distance the drone is from the window. $d = m\cos\theta$. Note that this calculation holds true for when the drone is in the dive position and is pointing down because cosine is an even function. This distance will help the drone navigate itself around the building, and it will also be used to find the vertical angle of the sprayer to maximize the sprayer's efficiency. This will be discussed in later sections.



Sprayer

This section analyzes various elements of the sprayer. It discusses the spraying speed and water pressure of water sprayed out of the sprayer. The operational limits of the drone are also briefly discussed. Next, this section moves into both vertical and horizontal angles the sprayer and drone must rotate to spray a certain part of a window.

Spraying Speed and Pressure of Water

This subsection finds the average speed of the water being sprayed out and the pressure with which the water is sprayed. All the discussions below are based on the assumption that the flow of liquid is constant. In this project, we use a pump capable of generating 1600 psi of pressure(functions at 210 psi for our purposes) and pumping water at a rate of 1.6 gallons per minute.

Spraying Speed

Assuming the rate by which water flows out of the pump is 1.6 gpm or 101 mL/sec, we can calculate the speed of the water flow in the pipe by dividing the rate of flow by the cross-section area of the pipe. This results in $\frac{101\text{cm}^3/\text{s}}{\left(\frac{\frac{7}{64}\cdot 2.54}{2}\right)^2\cdot\pi\text{cm}^2} \approx 1666\text{cm/s}=16.66\text{m/s}$. This is the speed of water in the pipe. Using the fluid continuity equation $A_1v_1 = A_2v_2$, where A_1, v_1 represent the cross-section area and fluid speed of the cross section in the pipe, and A_2, v_2 represent the cross section at the mouth of the sprayer. Plugging this in to find the speed of water that comes out of the sprayer (before hitting the angled slope that sprays water out), we get $\left(\frac{7}{128}\right)^2 \cdot \pi \cdot 16.66 = 0.05^2\pi \cdot v_2$ because the diameter of the sprayer is 0.1". This equation simplifies to $v_2 \approx 19.93$m/s. Because the speed leaving the sprayer before bouncing off the angled slope is 19.93m/s, we know the maximum speed of solution leaving the sprayer is 19.93m/s.

Pressure of Water

Based on this estimated liquid speed, the maximum altitude at which the pump can provide such flow of liquid can be calculated. The pump functions at 210 psi, which is the maximum pressure our pipe can hold safely. Utilizing Bernoulli's equation, one can obtain $P_1 + \frac{d_1v_1^2}{2} + d_1gh_1 = P_2 + \frac{d_2v_2^2}{2} + d_2gh_2$. Here, P_1, P_2 represent the pressure of water at two points, d_1, d_2 the density, h_1, h_2 the altitude, v_1, v_2 the liquid flow speed, and g the standard gravity.

Attached to Ground Plugging in 10^3 kg/m^3 for d_1, d_2, 16.66m/s and 19.93m/s for v_1, v_2 respectively, 210psi and 30psi for P_1, P_2 respectively, and 0 for h_1, we can solve for h_2. This results in $h_2 \approx 142$m. Since the limited payload of the drone limits the operational altitude of the drone to 88m, the 142m as calculated by the pressure constraint of the pipe is far more than sufficient in the case when the pump is on ground level.

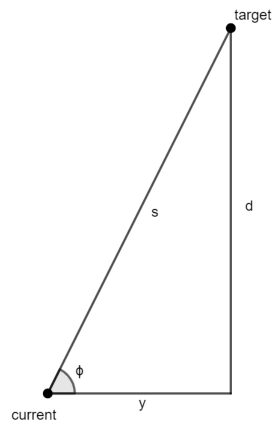
Attached to Roof When the pump is attached to the top of the building and runs the liquid pipe down, the lowest altitude at which the drone can function is almost completely dependent on the pressure, since the drone is not required to carry all the weight of the pipe. Let d_1, d_2 be 10^3 kg/m^3, v_1, v_2 be 16.66m/s and 19.93m/s respectively, g be the standard gravity, h_2 be 0, and P_1, P_2 be 0 and 210psi respectively. Solving for h_1, the drone can function up to 154m (around 51 stories) below the altitude of the pipe. Therefore, by shifting the pump system from ground level to the top of a building during intermissions of operation, this system is expected to be able to clean a building 242m (around 80 stories) tall.

Spray Location

With an algorithm, the drone will recognize a window and choose a spot on it to clean. It maps out the 2D coordinates of the window and uses its position in relation to the window to determine the vertical angle of the sprayer and the horizontal angle of rotation of the drone.

Horizontal Angle

This subsection finds the horizontal angle the drone must rotate. Let d be the distance the drone is from the window and y be the horizontal distance the drone needs to spray. ϕ is the angle we look for. From the diagram, it is clear $\phi = \tan^{-1}\frac{d}{y}$. Also, $s = \sqrt{d^2 + y^2}$. In this scenario, the total 2 dimensional distance travelled by the liquid before hitting the target is s, during which the liquid experiences a downward gravity pull. This is explored further in the next subsection.

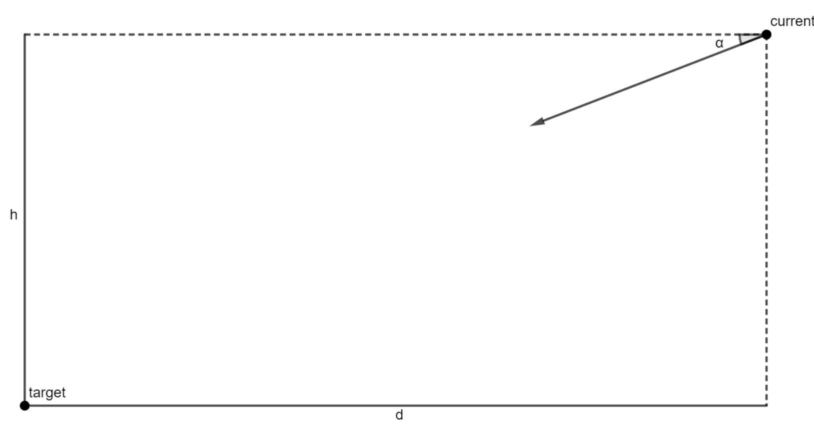


Bird's eye view of horizontal spraying mechanism

Vertical Angle of sprayer

This subsection aims to calculate the angle the sprayer must rotate vertically. It is essential to the ability of the drone to spray a window properly. By first assuming the pitch of the drone is zero, we find the angle the sprayer must rotate. Next, this equation is generalized to include the pitch the gyroscope measures.

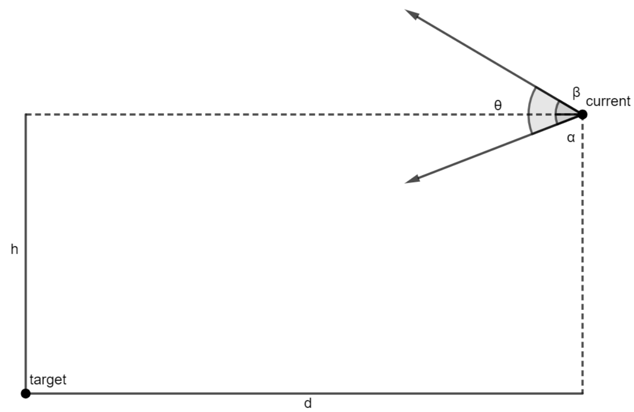
Perpendicular to Window



We start by assuming the pitch of the drone is zero. Let α be the angle we are looking for, h be the vertical distance down the drone must spray, d be the distance the drone is from the wall, v be the velocity of the solution sprayed, and g be the force of gravity. s is the total distance travelled by the liquid disregarding altitude. Letting t be time, we know the system $\begin{cases} s = vt\cos\alpha \\ h = vt\sin\alpha + \frac{g}{2}t^2 \end{cases}$ holds. We substitute $t = \frac{s}{v\cos\alpha}$ to the second equation, getting $\frac{s}{v\cos\alpha} \cdot v\sin\alpha + \frac{g}{2} \cdot \frac{s^2}{v^2\cos^2\alpha} = h$. Solving for α, we get $\alpha = \sec^{-1}\left(\frac{\sqrt{2}v}{\sqrt{\frac{s^2(\sqrt{-s^2g^2+2ghv^2+v^4}+gh+v^2)}{s^2+h^2}}}\right)$. Because this is a long expression for a flight control to calculate, we estimate $\frac{s}{v\cos\alpha} \cdot v\sin\alpha + \frac{g}{2} \cdot \frac{s^2}{v^2\cos^2\alpha} = h$, the equation before solving for α, to be $h = s\tan(1.05\alpha) + \frac{s^2 g}{2v^2}$. This assumes that h, s, and v are positive, like they would be during use. Solving for α, we get $\alpha = \frac{20}{21}\tan^{-1}(\frac{h}{s} - \frac{sg}{2v})$. Although this is not the exact value for α, it is a reasonable estimate considering the fact that it uses less flight control power and the original calculation did not account for air resistance and other environmental factors. The percent error in the estimation is only about 1-3%. Therefore, this estimation will be sufficient for our purposes. All variables on the right side of the equation are either calculated in sections above or will be calculated based on methods discussed above.

Not Necessarily Perpendicular to Window

The drone is not always perpendicular to the wall as we assumed in the previous subsection. Let the angle described in the previous subsection be α and the pitch of the drone downward as measured by the gyroscope be β. Let the total angle the sprayer must rotate be θ. This means $\theta = \alpha + \beta$ because they are both on the same plane. Plugging in what we estimated for α, we know $\theta = \frac{20}{21}\tan^{-1}(\frac{h}{s} - \frac{sg}{2v}) + \beta$, where all the variables on the right are calculated before this calculation. This function represents the angle the sprayer must rotate regardless of the pitch.



Spraying Solution

In the planning stage, there were several potential spraying solutions. All of these solutions would be diluted in water when sprayed for cleaning.

1. Pure Water
2. Windex
3. Palmolive Dish Soap
4. Finish Jet-Dry
5. Kaboom

The first property of these solutions tested was the ability for these solutions to dry without streaks. From previous knowledge, it was clear that the pure water would leave streaks when drying, so it was ruled out immediately. To test these solutions, they were diluted in water and poured onto a piece of clear plastic that mimicked a window. The plastic was then left to dry in the sun for approximately three hours. It was undisturbed and there was no rain that day. After the testing, the Jet-Dry rinse aid solution left almost no streaks, so it was the chosen cleaning agent. We have not yet determined the optimal solution between Jet-Dry and water for our system yet, but we will find one that maximizes the cleanliness of windows and minimizes the streaks left behind.