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Drought Monitoring with Drones
A Hundred Fields at a Time

Moyer, W., Patil, N., Toffoli, E., Hadi, N., Guan, A., and Goings, S.
Schools in Colorado, Texas, Florida, and New Jersey

August 2022

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I. Abstract

Drought frequency and severity are likely to increase due to global warming. Droughts already have a substantial negative influence on agriculture and the economy and finding ways to reduce their effects could have a monumental impact. Although NASA already has satellites deployed to collect drought data, these satellites are more for global drought indexing than local.

To alleviate droughts on a local level, this paper proposes the use of drones to map soil moisture, plant health, and other drought indicators. The proposed drone design is a fixed-wing UAV equipped with a hyperspectral camera, a LiDAR sensor, and an array of weather sensors. These tools will permit it to reliably capture the necessary data to enhance suggestions on improving drought management practices.

The collected data from the drones will be deployable in many ways, including for agricultural and non-agricultural applications. The hyperspectral camera has applications in monitoring the health of crops within a field to direct relief measures to the crops most in need. Thermal and LiDAR imaging can be deployed for locating leaks, predicting shortages of water bodies, and determining a field's water needs.

To implement a drought-monitoring drone, the recommended steps include building a prototype drone design that is equipped with the outlined instruments. The prototype drone could then be deployed to collect training data to guide a neural network that would provide interpretations and predictions from the data for users. After the prototype design is iterated upon, it will be ready for deployment and inform water management methods to serve the world in our battle against drought.

II. Introduction

A. Context

The root of the drought problem, like many problems, lies with global warming. Since 1880, the average global temperature has risen over 1.01 °C (2.13 °F) [1]. The cause of increased temperature resides with human activity, primarily the burning of fossil fuels. When the electromagnetic radiation from the sun strikes the earth's clouds and surface, much of the energy reflects back into space. However, some molecules – namely carbon dioxide, methane, nitrous oxide, and water vapor – absorb the energy as heat rather than permitting it to dissipate into space. The process of light energy being absorbed rather than reflected leads to the rapid increase of global temperatures (Fig. 1). NASA's Atmospheric Infrared Sounder (AIRS) has been recording record high temperatures, including a massive heat wave in 2021 [2]. Besides the direct warming of the planet, global warming also has many adverse ancillary effects, including amplifying the severity of droughts.

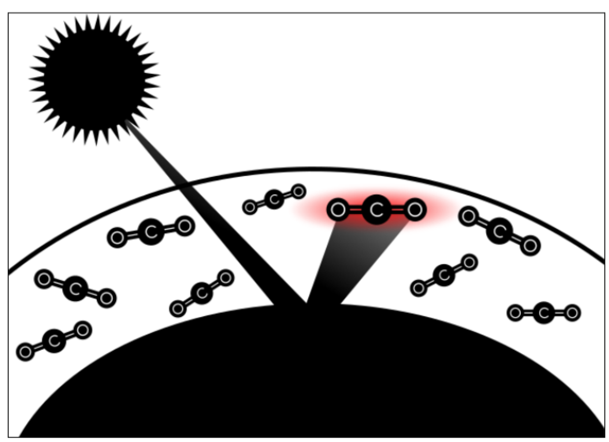

Fig. 1. Demonstration of carbon dioxide's effect on global temperatures

Droughts are defined as years with abnormally low water supply. They correlate with decreased precipitation, less groundwater and surface water, and detrimental effects on ecosystems and agriculture. In the United States, droughts currently occur primarily in the west, but they are likely to spread towards the east due to changing climate conditions.

As global temperatures increase, evaporation rates do as well. Increased evaporation is not only due to increased heat energy; warmer air can also hold more water vapor. For every temperature increase of 11 °C (20 °F), the maximum water holding capacity of the air roughly doubles [3]. A warmer planet will be a planet with less reliable water sources, as the atmosphere quickly absorbs available water. Additionally, warmer temperatures lead to lower rates of snowfall. Snowmelt can serve as a steady source of water for rivers and lakes; as snowfall decreases, so does the reliability of water supplies. Finally, climate change shifts weather patterns, which can lead places adapted for high precipitation to receive less rainfall [1].

There are some places that may receive greater precipitation and wetter conditions as a result of climate change. Global precipitation levels are rising (mainly due to the increased evaporation noted earlier), so not all regions will have increased drought. Rather, climate change correlates with wetter conditions in some places and dryer in others [4]. For the places with amplified droughts, it will be necessary to develop ways to adapt to a less forgiving climate.

B. Rationale

Due to the significant impacts, droughts are one of the costliest natural hazards, affecting many economies, environments, and causing health issues. With a cost of $9.6 billion in damages and repairs, drought is the second most expensive natural disaster behind hurricanes [5].

There are different types of droughts categorized into five basic approaches known as meteorological, hydrological, agricultural, socioeconomic, and ecological [6]. Drought is characterized by severity, the area affected, duration, and timing. Due to increased temperatures and altered rainfall patterns brought on by global warming and climate change, droughts have grown more frequent and severe in many areas of the world. Alteration in rainfall patterns may be caused by shifts in global wind patterns and increasing ocean surface temperature [7]. Therefore, these extreme droughts result in detrimental effects such as shortages of drinking water, food, and nutrition, poor air quality, diseases, and even instigating other natural disasters [8].

Drought is monitored through precipitation and soil moisture levels, drought-susceptible trees, lower water level sources (such as reservoirs, lakes, and ponds), extreme heat temperatures, crop damage, and destruction of wildlife. Precipitation levels are measured by the depth of the waterfall, using two systems known as the Standard Precipitation Evapotranspiration Index (SPEI) and the Standard Precipitation Index (SPI) [9, 10]. Drought can also be determined through relative humidity (RH), the percentage of water vapor in the air at a given temperature. It is quantified by dividing actual vapor pressure (Pa) with saturated vapor pressure (Ps), multiplied by 100.

$$\mathrm{RH} = \left(\frac{\mathrm{P_a}}{\mathrm{P_s}}\right) * 100$$

RH is a commonly used measure of atmospheric water vapor and depends on two factors (the absolute quantity of water vapor in the air and the air temperature).

Although monitoring moisture levels is effective for identifying and monitoring droughts, drought-susceptible trees can function as indicators of drought as well. For example, trees in shallow, rocky, and compacted soils are subjected to hotter and drier surface soils, affecting the plant’s capability to produce. Without adequate water, the plant’s photosynthesis is inhibited. The reduction in photosynthesis causes repercussions such as reduced plant and root growth and declined performance in the major component of plant cells. The soil's ability to hold water decreases so severely that tree roots can no longer intake moisture [11]. Although most soils still contain moisture, trees and other landscape plants cannot access this moisture. The extreme heat causes the reduction of transpiration which limits the cooling of leaves and tissues. Therefore, their hydraulic system is damaged as their roots extenuate. It takes days or even weeks for the trees to re-grow the root hairs necessary to take advantage of rainfall. The most notable changes in trees in distress are temporary and permanent wilting leaves, lighter green to yellow-green foliage, plants losing chlorophyll, bark cracks, and leaf scorch around the margins [12]. Through these changes in appearance, trees signal their water deficit. Searching for these signs is practical in determining where droughts are occurring.

When analyzing drought, indicators are effective instruments to track, monitor, and assess these problems. The drought monitoring system is classified based on current soil moisture content, streamflow, and recent precipitation. This system ranges from D0 - D4, determining the level of severity. Furthermore, D0 indicates that drought is not present but experiencing abnormally dry conditions. D1 is the least intense level of drought, whereas D4 is the most intense level of drought [13]. There are four primary indexes when assessing drought severity, known as the Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI), Standard Precipitation Evapotranspiration Index (SPEI), and Standard Precipitation Index (SPI). The PDSI calculates the relative dryness using temperature and precipitation data. It is a standardized index that ranges from -10 (dry) to +10 (wet) to determine the severity of the drought. One notable derivative of the PDSI is the CMI, which monitors the moisture supply in crop-producing regions in the short term. It was developed to assess short-term moisture conditions in major crop-producing areas. The SPEI is calculated based on the accumulated difference between precipitation and potential evapotranspiration [14]. Therefore, utilizing the climatic data determines the onset, duration, and magnitude of drought conditions. Similarly, the SPI is used based on the probability of precipitation on a time scale [10]. Positive SPI values indicate wet conditions and negative values indicate dry conditions. With the majority of SPI values currently being in the negatives, 55% of the United States is experiencing abnormally dry conditions.

III. Drought Monitoring Approach

A. Selected Solution

To help manage and combat droughts, this research recommends deploying fixed-wing Unmanned Aerial Vehicle (UAV) drones. Compared to blimps and quadcopters, UAVs can sustain higher speeds for comparable periods of time while being under the Federal Aviation Administration (FAA) drone regulations. These drones carry 11.3 kg. of payload and are powered by 3.6 kg. lithium-cobalt batteries at 660 Wh with an 89-105 kilometer range when fully loaded with 4.4 kg. of components. They have a wingspan of 3.1 meters and carry a Nickel Magnesium Cobalt Oxide Battery (NMC) with a density of 150-220 kW/kg. The selected solution proposes using UAVs equipped with hyperspectral cameras and high-resolution RGB cameras to help detect the composition of plants and their chlorophyll, nitrogen levels in the area, and soil moisture in areas of drought. The drones would also be equipped with a LiDAR sensor and a Forward Looking Infrared (FLIR) Model C2 camera for thermal infrared imaging, a thermometer for recording temperature, a barometer for recording pressure, and a hygrometer for recording amounts of water vapor in air and soil. They would also use Fraction of Absorbed Photosynthesis Active Radiation (FAPAR) technology to quantify solar radiation absorbed by leaves. They would utilize neural networks to transfer raw data into data suggestions that would be more useful for the farmer(s) or whoever is flying the drone.

B. Justification

The use of drones allows for more specific data in small regions. Satellites are currently one popular tool for monitoring droughts, but they typically only produce data with coarse resolution that is useful at regional rather than local spatial scales. For example, NASA's Soil Moisture Active Passive (SMAP) satellite has a radiometer that produces data at a resolution of

36 km, and when combined with radar measurements, the resolution still only reaches 3 km [15]. Satellites, once launched, don't have much flexibility with monitoring areas and methods. Drones have enhanced precision and higher flexibility.

Drones have an advantage over fixed sensors because they are mobile and able to cover larger areas of land with recharging. They can reach areas that would be difficult to reach by land and can get aerial views of an area.

IV. Drone Design and Sensors

A. Details and Function

The fixed-wing UAV design for our drone, called Model Drought Monitoring Drone 1 (DMD1), is efficient and permits recording data over a large area. The payload is the variable that impacts the distance and speed that the drone can fly. The hyperspectral camera can pick up on spectral signatures of whatever matter is in its field of view (FOV). With a high-resolution RGB (Red, Green, Blue) camera, the drone will be able to record field conditions and identify the specific spectral range of various objects. Additional sensors can be included to monitor drought conditions based on other variables and factors. The UAV can be customized by the user when they are ordering a unit to more specifically meet their needs, but the base equipment will include the spectroscopy equipment, LiDAR sensor, thermal imaging camera, thermometer and barometer.

1. Fixed-Wing UAV Drone

A fixed-wing UAV drone has several advantages over a quadcopter (which is a common choice for research applications) as a fixed-wing UAV's primary movement direction is horizontal, whereas a quadcopter's primary movement is vertical [16]. This makes quadcopters inefficient for covering large areas of land in a short amount of time. Even if the flight time of a quadcopter is the same as a fixed-wing design, it will still cover less ground because of their reduced horizontal velocity and lower battery capacity. Another advantage of the fixed-wing design is that it can carry a large mass (approximately 11.3 kg., excluding the battery weight) [16]. This allows for the use of larger and more accurate data collection systems on board as well as a large battery to permit a longer flight time. The components on the drone (excluding the battery) would mass nearly 4.4 kg. The components would include a LiDAR-thermal imaging camera unit with a mass of 2.7 kg., and the RGB-hyperspectral camera unit with a mass of 0.63 kg. The remaining 1.1 kg. of components would consist of the motherboard, driving, and wiring. The mass of the drone without any of its sensors or battery would be 3.6 kg. Its average flight distance while fully loaded would be between an 89-105 km range depending on the flight conditions. Without a payload, the drone is capable of up to a 161-km flight depending on the flight conditions. The battery design inside the fixed-wing plane would be a Lithium Nickel Manganese Cobalt Oxide (NMC) Battery, as this design has a density of 260-270 Wh/kg [17]. Providing a higher voltage to the motor, mounted to the fuselage, will allow the design to cut back a bit on battery consumption. A 24-volt supply would be sufficient for the UAV to travel at a constant speed of 125 km/hr [18]. Furthermore, the battery would be a large 1050 Wh battery with a mass of 5.1 kg. Housed in the front of the fuselage would be a circuit board that would coordinate power to the electronics and store data. A 1 TB micro-SD card may seem like the best choice, but at the speed at which the drone will be traveling, the constant data stream will be much higher than the write speed of a small micro-SD card. Instead, using a solid-state drive (SSD) is the best option as it has a relatively low cost and swift write speeds which would support the magnitude of data that the drone's sensors will collect [19]. A wingspan of 3 meters would be sufficient to allow the drone to sustain an efficient cruise speed, while consuming minimal power.

2. Spectroscopy

Using a hyperspectral camera and a high-resolution RGB camera (Fig. 2), the drone can collect data about chlorophyll content in plants, nutrient contents in the soil, and soil moisture levels 5 centimeters below the ground [20]. A hyperspectral camera will also be able to observe a greater wavelength of light, which allows for more accurate representations of chlorophyll values and groundwater concentration. The hyperspectral camera will be able to detect a plant's levels of chlorophyll, which is closely related to the plant's physiology, metabolic state, and capacity for photosynthetic growth [21]. The camera can use a hyperspectral reflectance and an ultrasonic sensor to measure the camera's distance from the observing object. Using this same technology and the use of an additional LiDAR & thermal imaging sensor, soil nutrient levels can be recorded and analyzed. To achieve this, the hyperspectral camera should have a pixel width of less than one square meter when the drone is at cruise altitude.

Fig. 2. Spectroscopy 3D design

3. LiDAR Sensor & Thermal Imaging Camera

Using a LiDAR sensor and a thermal imaging camera (Fig. 3), it is possible to accurately predict groundwater levels [22]. When paired with data from the spectroscopy equipment, soil nutrient levels are also predictable. The LiDAR sensor will help generate a topographic scan on top of which the thermal imaging camera's data can be superposed. With the topographic scan, the drought monitoring software can provide more accurate predictions on drought conditions. The thermal imaging camera will be crucial in measuring the ground temperature, to allow the drought monitoring software to predict locations and levels of groundwater. To achieve this, the thermal camera should have a pixel width of less than one square meter when the drone is at cruise altitude. It will also be important in collecting data on soil nutrients and their quantity, in conjunction with the spectroscopy equipment. Soil nutrient levels are predictable because the soil organic compounds that make up the electromagnetic radiation response have clear spectral characteristics in the visible and near-infrared ranges because they contain functional groups like C-H, -COOH, -OH, and N-H which are chemical compounds that make the soil composition [23]. This makes imaging spectrometry and proximal reflectance spectrometry useful for quantifying soil properties.

Fig. 3. LiDAR sensor and FLIR C2 Thermal Imaging Camera 3D design

4. 3D Prototype

The cumulative product of the project 3D prototype was created in Blender. The design for our drone, Model DMD1, was created based on research of the ideal drone type and instruments as outlined above, and it went through multiple iterations based on collective feedback. The prototype design (shown below in figures 4 and 5) outlines what the drone would look like if implemented.

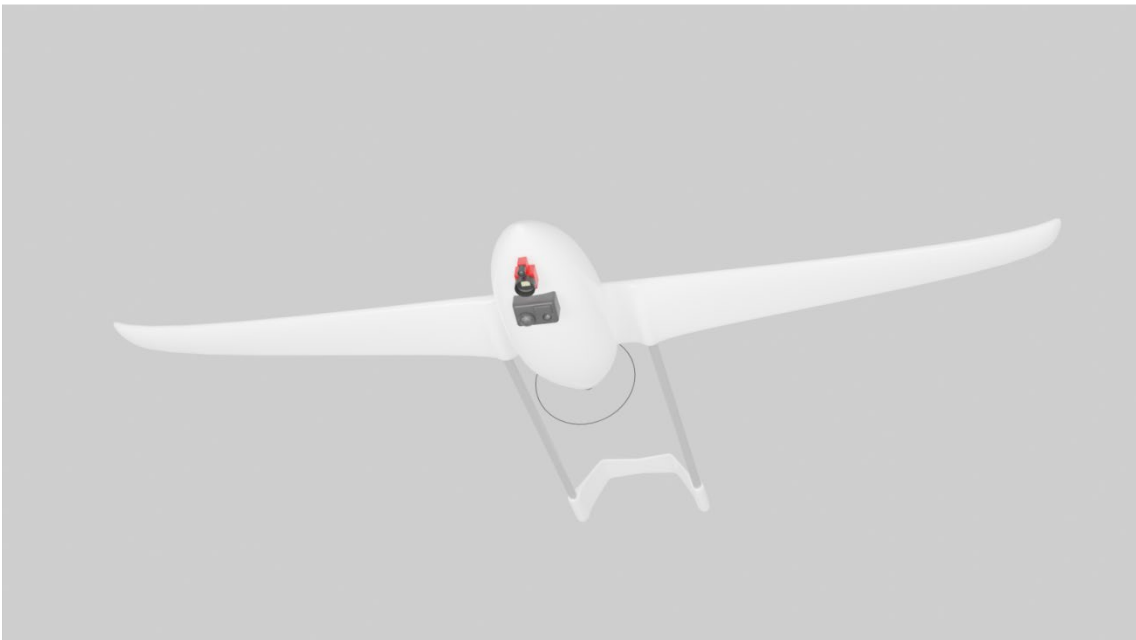

Fig. 4. 3D render of the Model DMD1 prototype

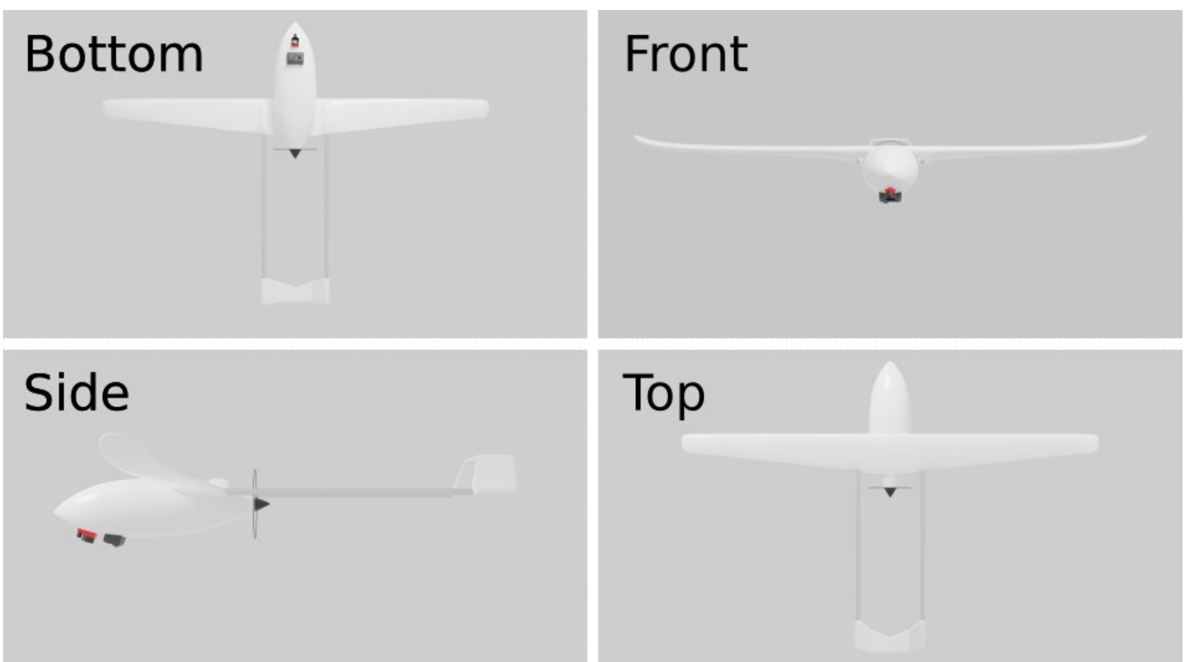

Fig. 5. Different views of the Model DMD1 prototype

Shown on the bottom of the drone's fuselage are the red RGB-hyperspectral camera unit and the gray LiDAR-thermal camera unit. The remaining instruments could be mounted inside the fuselage of the drone, along with the battery and motor. The propeller is depicted as a thin torus at the tail of the fuselage, but in implementation would have propeller blades. Shown below in Fig. 6 is the drone with some of its approximate dimensions. Although the product is merely a 3D prototype, it can be used as a basis for future physical iterations.

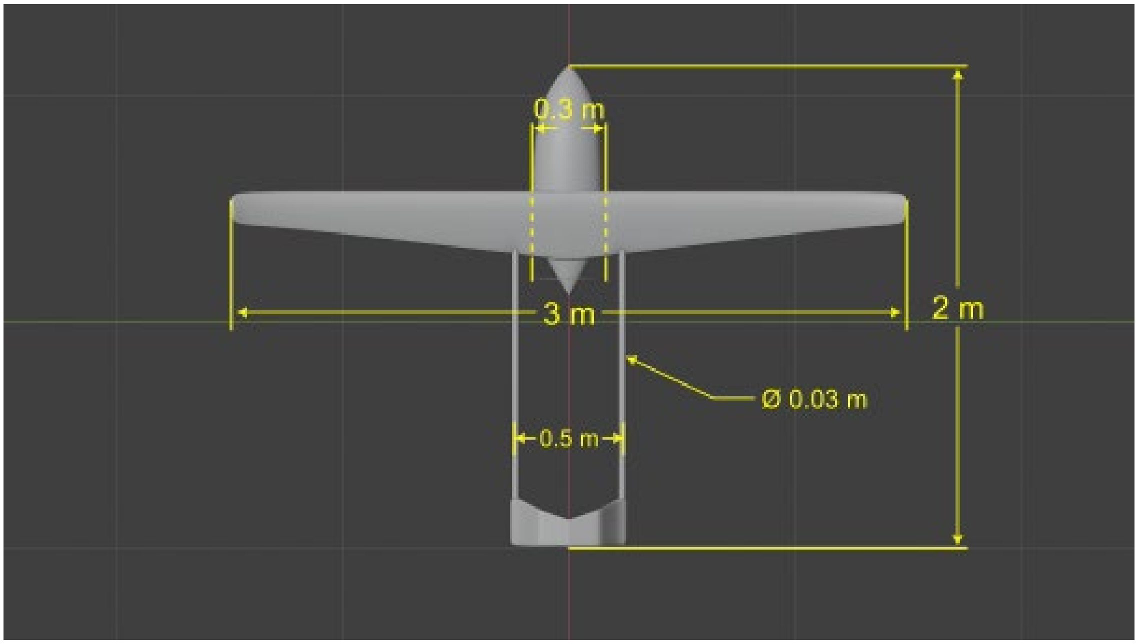

Fig. 6. Dimensions of the Model DMD1 prototype

B. Software

1. Navigation

Navigation is an integral component of UAV data collection since flight time is limited and the data must be collected over a large scale. The objective is to cover more ground by reducing overlap or gaps in the sensor's collection area. Using robot vacuum mapping software as an inspiration, using 3D Visual Simultaneous Localization and Mapping (VSLAM) technology could be the best solution for efficiently mapping the drone's flight.

Modern robot vacuums generally travel in straight lines to efficiently cover as much square footage as possible because there is a limited battery, just like with a UAV. Using such a navigation pattern, it is possible to simply set an area of land using satellite imagery and direct the UAV to collect data. Just as with modern robot vacuums, it is possible to set boundaries for the UAV. The onboard sensors could also aid in the drone's navigation.

2. Processing Unstructured Data with Neural Networks

Using neural networks to process the collected data would greatly improve the convenience and utility of the drone. Most of the drone's data will be unstructured data, which is data that is not easy to parse and interpret directly by a computer [24]. For monitoring droughts, the drone's unstructured data would be the pixel maps from the cameras.

To interpret unstructured data, traditionally human users would have to view the map to look for patterns. Thanks to neural networks, computers can interpret the data instead. Neural networks operate with a massive web of equations called nodes which are connected to each other and modify the data passing through them to convert an input into an output (demonstrated in Fig. 7). An untrained neural network will take in a series of inputs and convert them into a random output. However, by using training data to compare the actual output to the desired output, the neural network can incrementally improve its equations to be able to produce an output that is meaningful. Although neural networks are just systems of equations, they can become artificially intelligent because of how many layers and connections exist within the network [25]. It is also possible to develop several iterations of the neural network using different architectures, moving the neural map toward greater efficiency.

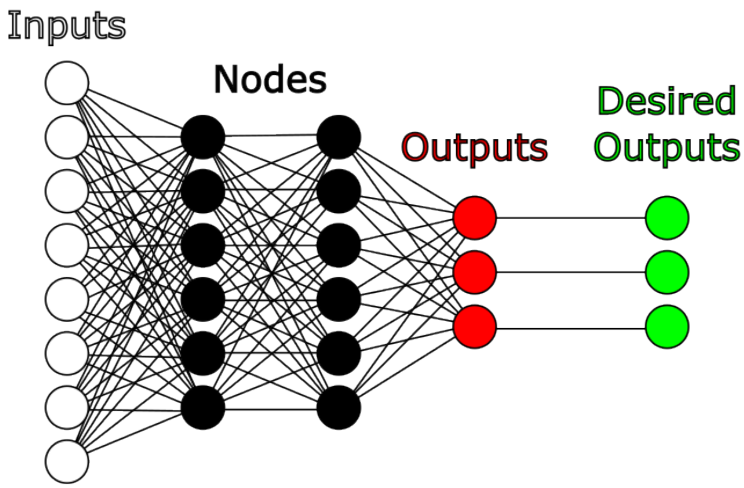

Fig 7. The structure of a neural network

A neural network could be used to identify features of the drone's readings to aid the user in interpreting the drone's data. For example, a neural network could use the drone's thermal imaging to identify areas of potential leaks and notify the user of their location and severity, which would be more efficient than the user manually looking through the data to locate leaks. Another example of the utility of neural networks is their use in predicting droughts. The drone's sensors would provide data that could be used alongside satellite data to better anticipate droughts to improve preparation measures.

The primary challenge with using a neural network involves collecting training data. The network needs an immense amount of data that includes both the inputs and desired outputs. The drone could collect the inputs itself, and the desired outputs could be collected with other sensors. With the example of a drone using thermal imaging to detect leaks, the outputs could be collected with on-ground sensors that find leaks themselves. After the drone has sufficient training data, and the neural network is complete, it could operate in areas without on-ground leak detection sensors. Hence, a neural network could greatly improve the accessibility and utility of the drone.

C. Drone Regulations

If these drones were manufactured and distributed around the United States, Federal Aviation Administration (FAA) regulations would apply to them since they are unmanned flying vehicles that could interfere with smaller, low-flying manned aircraft. All drones that are not registered by the FAA must fly below 120 m. For drones to get registered, they must be over 25 kg. and the owner/pilot of the drone must get a license before flying it (costs $175 dollars for initial test and $5 a year per drone to stay registered). Given that our drones would weigh less than 14 kg. total, they are ineligible for FAA registration and would be restricted to a height limit of 120 m [26]. Drones are only allowed to fly in open airspace and are restricted from interfering with wildfires and hurricanes. Since the proposed drones would be working in areas of drought, there is potential for wildfires to occur in areas that the drone would operate. Operators should notify emergency services of where they plan to fly the drone and take care not to enter areas under emergency conditions [27]. Drone flying is the only part of this solution idea that has regulations placed on it, so the other technology involved can be used as intended without any interference or licensing issues.

V. Drought Monitoring Approach

A. Agricultural Applications

There are many rural applications for the drought data that would be collected by the proposed drone. The applications discussed here either relate to agriculture or are broad-scale applications that cover a substantial area of land.

1. Groundwater Monitoring

It is important to monitor groundwater properly to ensure the sustainability of the water supply. This is especially important for rural residents, who are more likely to rely on groundwater from wells and are therefore more vulnerable to droughts if these wells run dry [28]. Proper management can prevent over-pumping and reduce the effects of droughts. Governments and other organizations could use the data collected by drones to help develop groundwater sustainability plans. The drones could provide information on groundwater levels over wide areas, and the water levels and underground water flow could be used to determine where to pump water.

2. Detect a Field's Water Needs

To conserve water, it is important to water only the areas of a field that need it. The drone data on plant health and soil moisture levels could be used to determine which areas have too much, just enough, or not enough water. Recommendations could be provided on which sections to water for maximum efficiency.

3. Monitor Water Flows

Drones could be used to monitor the flow of groundwater in specific ecosystems. This could allow for a better understanding of the dynamics of the water system in that particular area. This information could then be applied to predict droughts and to determine how best to alleviate them. Observing the patterns of water flow can also be useful in agriculture when making planting decisions. For example, the natural drainage of an area of land can affect which crops are suitable to plant depending on their tolerance of poorly drained land [29].

4. Detect Water Leaks

About 20 to 50 percent of water is lost through leaks in North America's water supply system and solving this issue could save money and billions of liters of water [30]. Drones could be used to detect leaks in water distribution pipes. This is especially useful for monitoring pipes that span large distances. To detect leaks, data such as soil moisture could be used, and the land could also be monitored for increased vegetation in specific areas, which could suggest a leak. Drones could also be used to detect leaks in irrigation systems on farms.

B. Non-Agricultural Applications

This drone is not only intended to monitor agriculture: its demand will likely grow over time in non-agricultural drought applications. The potential of droughts in the urban landscape mainly occurs from the breakage or damage of water facilities like those of dams, treatment facilities, piping, and many more. In the past few decades, drought applications have become obligatory from the extreme rise of severity in droughts worldwide [31]. Hence, the utilization of drought-managing drones on the urban scale is a requisite project that can be implemented with a wide selection of specific applications.

1. Monitoring and Measuring Stress and Pressures

To prevent droughts in the urban, non-agricultural environment, actions must be taken in monitoring and measuring the stresses and pressures that can cause catastrophic damage to the much-needed water facilities that cities and towns rely on. In most facilities, many people are needed to monitor that, thus, drones can easily take the place of humans and be implemented with software and instruments made to monitor and measure water facilities. Specifically, the Model DMD1's thermal cameras could monitor and measure the heat created from structural stresses or uplift pressures [32]. For example, if there is too much structural stress in the piping of a water treatment facility, major damage could occur. Hence, drones could be used to meticulously monitor, measure, and stop these disastrous breaks from occurring in water facilities.

2. Data logging of SWL

When the standard water level (SWL) of a body of water becomes too low, facilities that use its water no longer stay operational [33]. Moreover, the cities or towns that rely on that specific body of water must rely on a further or unreachable source. In a scenario where SWL becomes too low for use, a high potential for a severe drought occurs. Hence, utilizing drones equipped with an application to log and track SWL, a solution could be found in advance to stop an extremely low SWL from occurring.

3. The DamAT Project

The Dam Analysis Tool Project (DamAT project) is a system developed by the National Weather Service to allow forecasters to generate a failure forecast in a short period of time [34]. This software can be created and is meant to be generated, when information and data on the state of facilities like dams and pipelines are sparse. For instance, if a break has occurred in a dam and it is unknown where the break has occurred, drones that are equipped with the DamAT software can immediately notify people or even other drones that help is needed in identifying and fixing a problem in the facility. Using the DamAT software on drones is a simple device that eliminates a large gap in the process of preventing and stopping broken or damaged water facilities, ultimately putting an end to a large cause of droughts in the urban landscape.

C. Desirability, Viability, Feasibility

To create a profitable and valuable solution, we must consider the factors that would determine whether our product would be realistic.

1. Desirability

Given that global warming has led to the increase of harsh droughts, an affordable way of managing these weather conditions would be valued around the world. As previously stated, the global heat index is rapidly rising and is affecting supplies (such as clean water and food) that are necessary for human life. Droughts are intense strains on global economies and quality of life, but they do not have to be. Deploying drones as a solution to the drought issue could alleviate the burden of food and water shortages for people globally.

2. Viability

Because of the many abilities of this drone, it should have a diverse area of application, making it extremely profitable given the amount of area that would be positively affected by its many uses. Though the final cost of the drone could be expensive, a mass-produced version of the drone could come at a lower price. The viability of the drone extends beyond commercial utility. These drones could also be valuable for informing water use policies and governmental drought actions.

3. Feasibility

All the technology that this drone uses is already currently used for agricultural applications and is already currently mass produced as individual parts. Drones are becoming more popular and beneficial for many different national/global uses, so they are becoming more common to mass produce and fly [35]. The calculations completed in the *Drone Design and Sensors* section suggest that the recommended instruments would fit with ease on the UAV, with reduced challenges for deployment.

VI. Concluding Remarks

A. Next Steps

To bring this research to completion, the drone must first be engineered to operate effectively. Possible engineering steps to take are as follows.

1. Proof of Concept Testing

The proof-of-concept testing step involves constructing or purchasing each involved instrument and machine and checking to ensure that they function as needed for the project. For maximum utility, the drone should have the 11.3 kg. carrying capacity and the 88-105 km range mentioned in the *Details and Function* section IV-A. The cameras should have a pixel width of less than one square meter when the drone is at cruise altitude to record accurate measurements.

2. Prototype Construction

After the recommended materials are collected, an initial prototypal drone can be constructed. The prototype can be constructed in whichever method is deemed most appropriate, but the FOV of the cameras should be maximized and the drag from extruding elements should be minimized. The details on the build of the drone were featured in the *Drone Design and Sensors* section.

3. Prototype Testing and Training Data Collection

The prototype should be rigorously tested for durability. In the prototype testing, it will be beneficial to collect training data for a neural network. To collect the training data, it is important to first identify which ways a neural network could interpret the data that would be the most useful. Example use cases include having the neural network determine which elements of a field are being underwatered or overwatered, where leaks are occurring, or predicting the onset of drought. Then, collect a large amount of data with the drone paired with data on the desired use case. For example, for determining which areas of a field are suffering from lack of water, collect data from the drone and feed it into the input of the neural network. Alongside this, collect data on areas where the field is suffering from lack of water (potentially using fixed sensors), and feed this into the neural network's desired outputs.

4. Further Prototype Iterations and Progression to Final Product

After identifying flaws with the initial prototype hardware and software, it will likely be necessary to modify the drone to fix the areas of issue. Modifying the drone would take multiple iterations and likely end up with a final product somewhat different than what was proposed in this research. After modifications, the drone will likely be ready for deployment, and it will be time to find consumers. The drone is intended to be operated from a governmental standpoint, assessing many fields at a time to inform drought aid efforts, but it can also be deployed in a commercial setting to help farmers maximize their crop yields. This project may be able to aid tens of thousands of people in their fight against drought.

B. Broader Implications

The applications of drones equipped for drought monitoring extend well beyond the United States. For example, the Horn of Africa has been suffering from its worst drought for 40 years. Currently, people's main mechanism for dealing with these droughts involves applying coping strategies, like moving or selling cattle [36]. Better technology to address these droughts may prove invaluable for these communities. However, the implementation of drone technologies in developing countries may not be as straightforward as in the United States. Drones would need an energy source, maintenance, and funding. Additionally, monitoring droughts in Africa may have limited impact without developed infrastructure for irrigation. However, drought monitoring drones would not be the first drones to be deployed in Africa. There is a company that seeks to serve Africa's medical needs by dropping supplies with drones in Rwanda. Supply drop drones are especially impactful due to poor road access in the area which would lead to the same supplies taking several hours to arrive by land. The deliveries in Rwanda usually occur in less than half an hour [37]. If the principles of drought management are carried forward in a way that is cognizant of the unique needs within Africa, it could have an immense impact.

Additionally, similar drone technologies as the ones discussed to address drought in this research could be applied to similar situations. Spectroscopy could be utilized to detect when plants are stressed due to a variety of different reasons, not just drought. Moisture monitoring can work to tackle signs of flooding. Thermal imaging is already implemented for wildfire management, and search and rescue missions [38]. Drones can provide a useful vantage point and will likely play a critical role in a future that is better equipped for major crises.

VII. References

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