An Autonomous Pollution Detection System for Water Bodies Using Drones

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Figure 1: the drone

Figure 2: the laboratory

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Abstract

How can an autonomous drone be used to assist in the detection of contamination in water sources?

This work explores a system design and implementation for the collection and processing of liquid samples without human intervention.

Traditional methods for quality testing of water bodies are often slow and expensive. These characteristics limit the frequency at which these tests can be performed, often leading to late detection or complete oversight of water pollution. This delay can result in severe environmental damage and costly remediation efforts.[1]

This research introduces an autonomous system that uses a drone and portable analytical labs for frequent, cost-effective, and autonomous water sampling, testing, and analysis. They can survey multiple water bodies within a 10km radius.

The development of the autonomous drones to collect water samples from various sources at conditionally predetermined intervals and transports them, was carried out by a different team (see figure #1 on the cover page). The present part of the project addresses the development of an autonomous analytical lab, where tests are conducted to analyze four indicators which characterize water quality (see figure #2 on cover page). If the results exceed the specified regulatory threshold level (RTL) set by the user, an alert is activated. The study explores a process that conducts quick statistical analysis of the four indicators to assess the probability of pollution of the water body. If pollution is detected, the system recommends conducting further tests in a traditional lab to determine the specific nature of the contamination.

The current water inspection methods for largely inaccessible water bodies

At present water quality monitoring is a predominantly human-led task that involves the collection and analysis of water samples across different locations. This task is achieved by different methods such as remote sensing, on-site installed sensors, and field personnel. The latter moves within water bodies, manually extracting the samples and ensuring their safe delivery to assigned laboratories. This traditional method is prone to human error, and weather variability, especially in hard-to-reach areas or hostile environments.

While field operators can carry out preliminary field tests, once the water samples reach the laboratories, they undergo a series of rigorous testing procedures aimed at detecting any presence of harmful microorganisms or chemical contaminants However, the laboratory testing phase is time-consuming and resource-intensive, often taking weeks or even months to finalize. Consequently, the test results are not immediately available due to the complexity of the analysis procedures and the sheer volume of samples that need to be processed.

The frequency of water sample collection is found to be the underlying issue due to the dependence on human inspectors. The sporadic sampling schedules, may lead to an overlooked contamination event, posing serious health risks to the dependent communities.

Water quality and ecological risks in European surface waters (2021)[2] revealed a clear link between a country's monitoring quality index and its ability to successfully detect contaminants. The issue with the other methods further complicates the situation by introducing expensive process of installing infrastructure of persistence unmovable sensors on-site which still requires harvesting, and the limitation of other methods such as remote sensing using satellites. Given the enormity of the task at hand, inspectors can revisit water sources only at intervals of weeks or months, contributing to the lag measure, which, in many cases, is determined by their workload and permission restrictions. Recent IOT (Internet of Things) allows connectivity to remote sensors, but those methods are limited by radio transceiver's range usually a few kilometers and still require an in-situ human operator to arrive with a radio frequency (RF) data harvest device. More work has been done combining the mobility of a drone and remote RF sensors,[3] yet this method requires multiple technologies working in harmony and physical in-water or over-water[4] sensor installation.

Overall, while the current system of regular water source detection has served us well for a considerable period, it is increasingly evident that a more efficient and reliable method is needed. As the world grapples with growing environmental concerns (European Environment Agency, 2023)[5] and increased demand for water resources, innovative solutions using technology, such as remote sensing and AI-powered analysis, may prove instrumental in revolutionizing how we detect and manage our water sources.

High costs associated with frequent sampling pose another formidable challenge. Carrying out manual sampling at such frequency would mean incurring substantially increased costs, which could potentially exceed the financial resources that the authorities are willing or able to allocate for this purpose.

Existing laboratories are often already stretched thin with the volume of tests that they handle and increasing this volume exponentially would likely result in bottlenecks and errors.

Given these limitations of manual sampling, the necessity for an innovative, efficient, and proactive solution to monitor water sources becomes starkly apparent. The urgency of this issue is only likely to increase with time, as pressures from industrialization, population growth, and climate change continue to threaten our water resources.

Research Objective

The overarching aim of this research is to develop a comprehensive system capable of consistently monitoring multiple water sources at high frequency and minimal cost. This system, designed to operate autonomously, will eliminate the need for human intervention in routine water quality testing procedures.

An integral part of this proposed system is its ability to rapidly assess the likelihood of contamination within a given water sample. Using advanced sensor technology and sophisticated data analysis algorithms, the system can yield preliminary contamination insights within mere minutes of collecting a sample. This near-real-time response capability presents a significant improvement over those current methods, which often involve extended time frames spanning hours to days for laboratory analysis. Implementing such a system, can contribute to the broader goal of sustainable water management, preserving the health of our communities, and safeguarding our planet's future.

Proposed Solution

The proposed solution integrates the use of autonomous drones and a mobile laboratory setup. The advanced system is designed to enable frequent, low-cost testing of water bodies with minimal human intervention.

Each water body within the system's operational area will be subject to several tests daily. An autonomous drone will be assigned the task of retrieving water samples, which not only makes the process efficient but also eliminates the human risk factor associated with accessing remote or hazardous locations (see figure #1 on the cover page) After the collection, each sample will be transported rapidly to the mobile laboratory for initial analysis.

Although the system is not equipped to specifically identify the contaminants, it will effectively monitor for abnormalities of four parameters, which are indicative of potential contamination. The ability to identify a possible deviation from the norm is a critical first step in responding to water quality issues. If any abnormalities are detected, the sample will be marked for further analysis and promptly shipped to an external, more equipped laboratory.

By employing an autonomous drone and mobile laboratory, the frequency of sampling can be increased, the time it takes to identify potential contamination can be reduced and the overall cost of maintaining water quality can be decreased, all while requiring minimal human intervention.

Herein the proposed process diagram

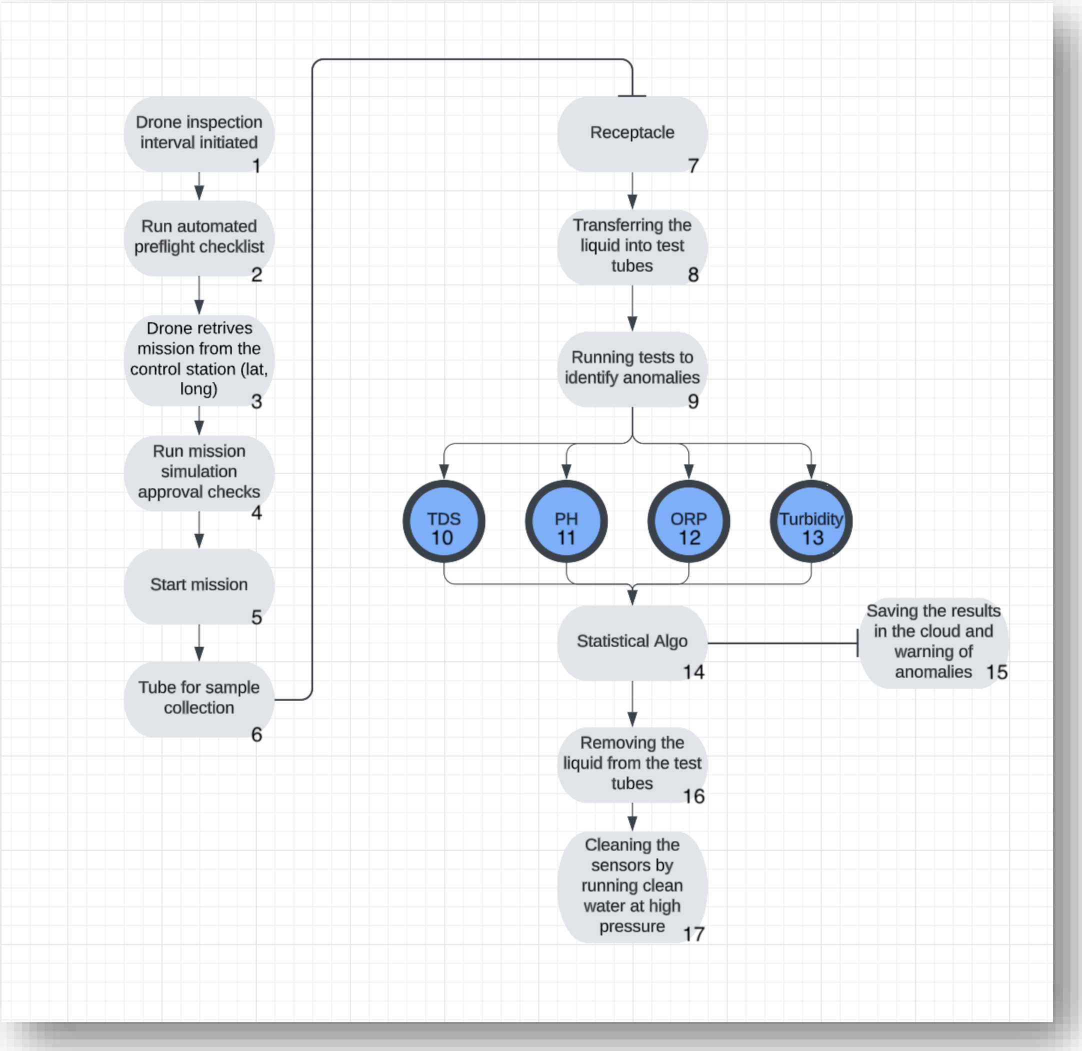

Figure 3: Proposed system flow chart

The flow chart depicts the overall operation of the proposed system. Steps #1-#6 deal with the drone activity and was addressed by a different team. The present study is focused on steps #7-#17 dealing with the mobile laboratory, as detailed in the following sections.

Overview of the System Operation

The drone, a key component of the proposed solution, utilizes a specialized mechanism equipped with a roller and a test tube to collect water samples from various sources. Once a sample is collected, the drone transports it to a designated container within the mobile laboratory, providing a smooth and efficient means of moving samples from their source to the analysis site.

The mobile laboratory is designed with a network of pipes, pumps, and valves that effectively distribute the water sample to various test tubes. Each of these test tubes is equipped with a unique sensor calibrated to detect any abnormalities in values that may signal potential contamination. By adapting the volume of the water sample to suit the specific test, the system ensures accuracy in its analysis and results.

The system operates on a continuous monitoring basis, always checking the sample data against predefined norms to identify any deviations. If an abnormality is detected, the system triggers an immediate response by sending a direct message to the relevant authority responsible for the water source. This message contains not only a notification of the potential contamination but also detailed sampling results, allowing the authority to conduct a more in-depth investigation promptly.

This innovative solution, combining automation and real-time data analysis, potentially advances water quality monitoring. Herein a description of the conducted test done to check and improve the mobile laboratory operation.

Description of the Performed Tests

The test was conducted at the UAV laboratory of the “Kfar Hayarok” Highschool compound. Test were performed at room temperature and an environment clean from contamination. Several consecutive tests were done at $28\ degrees\ [^\circ\mathrm{C}],$ in an open-air environment to further asses the practicality of the prototype system.

The following figure (see figure #4) schematically presents the assembled system used to validate the feasibility of the mobile laboratory. In the sequel the various parts are described in detail.

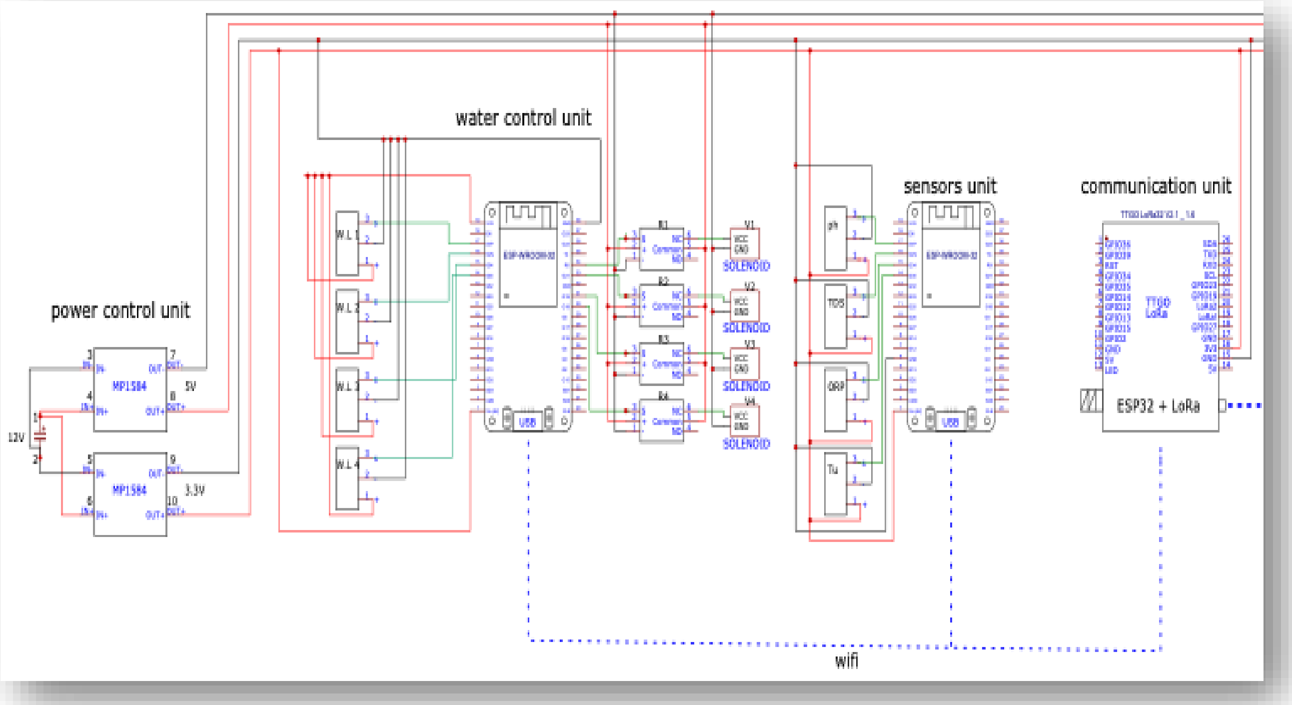

Figure 4: System Architecture Diagram

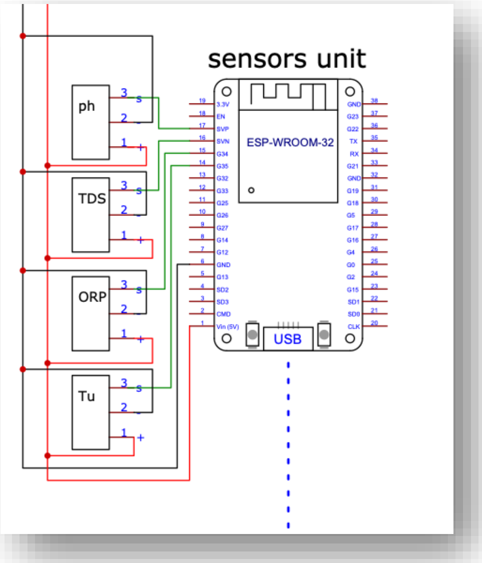

Figure 5: Sensor Unit Diagram

Because macrobiotic and chemical tests often require human intervention, which are slow and expensive, four quick and affordable physical tests were chosen to be carried out. Each test addresses an indicator which can be easily measured, as explained below. The basic assumption is that abnormalities in the indicators values reflects the potential presence of contaminants. The abnormality is relative to clean water values, which are measured in the calibration. Using statistical methods to analyze data, the study aims at predicting the likelihood of pollution. If potential pollution is detected, conducting further tests in a conventional lab is suggested to identify the nature of the pollution. Herein a list of the envisaged tests.

(1) ORP (Oxidation-Reduction Potential) measures the ability of a lake or river to cleanse itself and break down waste materials, such as pollutants, plants, and dead organisms. When the ORP value is high, it indicates a high concentration of oxidizing agents in the water. This means that bacteria responsible for decomposing dead tissues and pollutants can work more efficiently. Generally, the higher the ORP value, the cleaner and "healthier" the lake or river is assumed to be. However, even in healthy lakes and rivers, there are cases of low oxidation-reduction potential (and therefore lower ORP values), near the bottom sediments of the water body. The reason for this is that there are many bacteria in the sediment area that consume a significant amount of available oxidizing agents. Thus, sampling shall avoid the bottom zone of the water body.

ORP depends not only on the amount of dissolved oxidizing agents in the water, but also on other alkaline substances that function similarly to oxidizing agents. Although of indicative nature, oxidizing agents and other elements that contribute to a higher ORP value help facilitate the "digestion" of unwanted materials and substances in the water, such as pollutants and dead tissues. A low ORP indicates the accumulation of substances that cannot be easily cleaned or broken down, which is also unhealthy for fish or insects in the environment. Generally, ORP is measured by the using of an inert metal electrode (platinum, sometimes gold), which due to its low resistance will either give up electrons to oxygen or receive electrons from a reductant.

(2) TURBITY is a measure of the particle density in a solution. High turbidity can result from suspended matter, silt, algae, plant debris, melting ice, sediment, wood ash, or chemicals. Turbidity increases in rivers and lakes primarily due to floating algae, soil erosion from banks into the water, fires, or industrial activities such as mining, logging, or excavations.

Turbidity in rivers and lakes can vary throughout the seasons. For example, large rivers can have very low turbidity during the winter below the ice, but turbidity can dramatically increase during snowmelt when water carries soil from the land into rivers and streams. High turbidity in rivers can be caused by natural events such as heavy rainfalls, snowmelt, ice melting, or windstorms. However, high turbidity in rivers can also result from human activities in upstream areas. For example, trees cutting facilitates washing of soil to into rivers, leading to increased turbidity. Improper mining activities can also release large amounts of sediment and rock material, which can be washed into nearby rivers, lakes, and streams, increasing turbidity.

High turbidity, depending on the season, can have negative impacts on lakes or rivers. Dense algae blooms in lakes at the end of summer can block the light needed for other plants to grow. It can also have implications for aquatic life, including fish that feed on these plants. High turbidity due to algae blooms can also affect fish because when large amounts of dead algae decompose, the available oxygen is consumed, leaving less oxygen for fish. Large amounts of suspended sediments or clay can clog fish gills directly. High turbidity can also impede the vision and prey detection of fish, and they may bury and suffocate eggs laid on the bottom of lakes and rivers. Harmful pollutants and bacteria can also be associated with the particles causing turbidity.

Therefore, an abnormally high level of turbidity may indicate potential contamination. Turbidity is usually measured by sending a light beam into the water to be tested. This light will then be scattered by any suspended particles. A light detector is placed at (usually) a 90-degree angle to the light source and detects the amount of light that is reflected back at it.

(3) TDS The term "Total Dissolved Solids" refers to the total amount of inorganic and organic substances dissolved in a specific volume of water, including minerals, salts, metals, cations, or anions. Generally, as the TDS value increases, there are more dissolved solids in the water, indicating lower water cleanliness. Therefore, the TDS value can serve as an indicator reflecting water quality.

In the definition, dissolved solids must be small enough to pass through a filter with a pore size of 2 micrometers. TDS concentrations in water sources help us assess the water quality in freshwater systems. Water with a high TDS concentration may indicate high levels of various ions that can indeed be of health concern, such as aluminum, arsenic, copper, lead, fluoride, and others.

To measure TDS levels in water, its relation with the electrical conductivity of dissolved ionic solids is used. The electrical current, which is measured by a TDS sensor is presented as sodium chloride in ppm or in conductivity units of mg/liter or µS/cm.

(4) PH is a parameter that can be measured between values of 0 to 14, under the condition that the solution concentration does not exceed 1M. Solutions with $pH < 7$ are acidic, while those with $pH > 7$ are alkaline (basic). A pH meter is a device that measures changes in the activity of hydrogen ions (H^+) in a solution.

PH abnormal values relative to the standard $PH = 7$, is indicative of presence of harmful substances.

All these parameters were assessed by using sensors that convert signals into values of the pertinent parameters.

Calibration

In order to quantify the level of deviation of the indicators' values, the sensors used were calibrated against clean water or solutions with different additives. Herein the list of such solutions.

Distilled water: sensors displayed normal values, as expected. They are used as a base line to detect abnormalities.

Drinking water: the PH sensor and TDS sensor could be validated for quantitative results, as explained in detail in the following.

Then the system was tested with (i) drinking water with food colorants (two samples); (ii) drinking water with vinegar; (iii) drinking water with baking soda; (iv) drinking water with soil; and (v) drinking water with coffee. The last sample (vi) was taken from the local stream near the school. All the samples displayed values deviating from the normal ones, as detailed in the following.

All sensors must be calibrated to function correctly. To calibrate the sensors, the values of indicators for distilled water were used as standard. In the following a description of the results for different sensors.

Water level sensors: Since each test requires a minimal quantity of water, it was needed to measure the liquid level in each tube. The water level sensors were easy to calibrate. Marked glass tubes were used to perform the tests, so it was straightforward to calibrate it by introducing different volumes of water to each tube, reading the values from the sensors to the controller, and calibrating the system so that it converts the voltage correctly from the controller input (0V - 3.3V) to the volume of the water in each tube.

PH sensor: purified water was used to calibrate the sensor to the baseline (PH 7). Then an acid standard (PH 2.4) and a base standard (PH 8.4) was used. Having the baseline (7) and two standards enabled us to calibrate the linear dependence of voltage on PH, so that the sensor was calibrated completely. Then the sensor was tested three times with the acidic standard and three times with the base standard to validate it.

Turbidity sensor: The turbidity sensor was calibrated only partly because of a lack of solutions of known values. The baseline was calibrated based on distilled water. Then a formula from the literature was used to convert the voltage to the turbidity value. The sensor was tested with two different food colorants and got consistent results (the darker color gave higher results than the lighter color). Still, the formula could not be used or validated quantitatively because there wasn't the actual value of the colorant (it was not an official standard). The sensor can be trusted for the quality result (the sample is not clean water), but the quantitative result cannot. Therefore, a final calibration and validation shall be performed with an official standard.

TDS sensor: There weren't also official standards for the TDS sensor. However, purified water was used as one point and drinking water as the second point so that both the baseline and the curve could be calibrated. The value of the purified water was set to 50 ppm and the drinking water to 500 ppm. Therefore, the coefficients for a linear conversion from voltage to TDS value could be calculated. However, this is not a fully precise calibration because there are no real TDS value of our drinking water, and the 500 ppm for drinking water assumed. To complete the calibration and validation, at least one official additional standard for TDS is needed additionally to the purified water.

ORP sensor: For the ORP sensor, there weren't any standard or reference. Therefore, drinking water was used to give a consistent result. However, this sensor must be calibrated and validated with real additional standard solutions to obtain trustful results.

The implemented procedure and measurement results

Water level sensors: more than 20 tests were conducted to reach a satisfactory calibration of the water level sensors and the corresponding volumes.

First, the system was challenged with a too-small sample, and then with a too-large sample. Both scenarios are real live scenarios because the drone cannot always sample a precise volume of water, and the water loss while pouring the water from the drone to the tank cannot be predicted. The system worked as expected in both scenarios. Once there was not enough water in the tank, the system used only a few tubes (and tests) based on the available water volume and reported the error on the dashboard. Once too much water was in the tank, the system used the required amount to perform all tests and released the rest via the electric valve as expected.

PH sensor: after calibration with two standards and purified water, the sensor was tested with drinking water, vinegar, baking soda, and water from the stream next to the school together with retesting the standards (acid & base). All tests gave the predicted results, although there weren't precise values for the drinking water and the stream water to compare.

Turbidity sensor: after calibration, the turbidity sensor was tested with two samples of water mixed with food colorants. The darker food colorant gave a higher value than the lighter food colorant as expected. However, the actual value couldn't be validated (just the relative value) because no standards were given.

TDS sensor: after calibration, the sensor was tested with stream water and with coffee dissolved in drinking water. The stream water gave a higher value than the purified water, and the coffee gave a higher value as expected. Again, the values could not be validated due to a lack of standards. The purified water gave the expected value.

ORP sensor: the ORP sensor was tested with drinking water, purified water, and stream water. The sensor gave different values for each sample, but due to lack of standards or a reference to compare the results, this sensor was not calibrated or validated.

Discussion and conclusions

Different configurations to meet different environmental needs

One of the remarkable features of this laboratory is its adaptability. It can be tailored to meet the unique needs of different locations, considering the varying geographical, industrial, and environmental factors that could influence water quality. For instance, if a particular water source is situated near a factory known to produce specific contaminants, the system can be customized to include tests specifically designed to monitor these contaminants. This adaptability allows for more precise and relevant results, enhancing the system's effectiveness in identifying potential threats to water quality.

The mobile laboratory that forms part of this system is also highly adaptable. Depending upon the region's needs, different tests can be added, removed, or adjusted within the laboratory's repertoire. This flexibility ensures that the system remains relevant and effective regardless of changes in local circumstances or emerging contamination threats. This means that the system can remain current and useful in diverse settings and over time, despite changing environmental factors or pollution sources.

However, there is a key consideration to bear in mind in the system's operation - the balance between the number of tests conducted and the volume of water samples collected. The system's capacity to perform a wide range of tests is counterbalanced by the need for a sufficiently large water sample to conduct these tests accurately. As the drone collects larger samples to accommodate a broader range of tests, it may result in a trade-off where fewer samples can be collected from different locations due to weight limitations.

Thus, strategic planning and decision-making will be necessary to optimize the system's operation. It will involve weighing the benefits of conducting a wider range of tests against the need to monitor a broad number of water sources. Nevertheless, this system's adaptability and flexibility promise a significant improvement over traditional, manual water quality monitoring methods, representing a valuable tool in our efforts to safeguard the health of our water resources.

System activity in large areas

In regions with extensive water bodies or multiple distinct water sources, this system can easily adapt to effectively cover such vast or diverse areas. This adaptability is made possible through the flexible use of multiple drones working in concert or a single drone servicing several mobile laboratories as required. For instance, multiple drones can be deployed to sample different areas of a large water body, providing comprehensive coverage, and improving the chances of detecting contamination. This approach allows us to precisely locate the pollution source, thereby facilitating targeted remediation efforts.

Moreover, the system's operational flexibility extends beyond just the number of drones used. Drones can be strategically directed to different sampling stations based on factors such as load capacity and sampling schedules. This ensures efficient use of resources and optimizes the system's operation by balancing the workload between drones and laboratories, thus maintaining consistent monitoring coverage. By adapting to the specific needs of each area, the system ensures comprehensive, effective monitoring of water quality regardless of the region's geographical or logistical complexities.

This study shall be regarded as a first step toward applying the proposed drone-laboratory system to widespread application. Thus, design and use of the single drone and laboratory shall be tested in a water body as to check operation under field conditions. Once successful, the next step shall be the use of a number of drones and laboratories in order to cover a large water body or a few water bodies.

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