

Hydrone: IoT Enabled Water Quality Monitoring for Lake Conservation Management using a UAV

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### 1. Introduction

Eutrophication or algal bloom is prevalent in Malaysian inland aquatic bodies such as lakes and ponds which hinder the performance of its ecosystems (Sharip & Suratman, 2017). About 60% of Malaysian lakes suffer from eutrophication because of the organic nutrients (a byproduct of human activities) present in the water (NAHRIM, 2009). To address this issue, water sampling has to be carried out at regular intervals to detect the degradation of water quality at early stages so that it can be prevented. Currently, for lake sampling, trained personnel has to use boats and hire safety officers for the fieldwork. They need to collect large volumes of water samples and transport them back to the laboratory to test algae and nutrients present in the water (Azizul, 2019).

In situ water parameter sensing equipment that measures the physicochemical properties of the water are also used sometimes alongside water sample collection. Water quality parameters such as pH, Dissolved Oxygen (DO), Electrical Conductivity (EC) and temperature are measured on-site and the samples are used for bacteriological analysis in the laboratory (Al-Badaii et al., 2013). Often the water quality sondes used in situ measurements are quite expensive and usually not IoT enabled. There are several issues when it comes to sampling remote water bodies such as transporting equipment, boats, and people to the site which is extremely challenging if the site is far away.

UAV drones gained popularity recently in environmental monitoring tasks such as geothermal environments (Nishar et al., 2016), surveying coastal regions for topological mapping (Turner et al., 2016) and marine wild-life monitoring (Linchant et al., 2015). Drones are also used for various water sampling extensively by Koparan, Koc, Privette, & Sawyer (2018, 2019), Esakki et al., (2018), Detweiler et al., (2015) and many others. The ability of drones to carry sensors and access remote locations rapidly makes it quite attractive for remote monitoring applications (Beloev, 2016). Behmel, Damour, Ludwig, & Rodriguez (2016) in their review of water quality monitoring strategies suggested drone attachable IoT enabled sensors to optimize the monitoring process. They also stress the importance of the timely delivery of reliable data to decision-makers, watershed managers and other stakeholders which is only possible through real-time data collection using IoT enabled sensors.

A cost-effective, IoT enabled multiparameter sonde will be designed and developed in this study which will be mounted on an UAV-drone to provide physicochemical properties of water in real-time. Temp, EC, DO and pH are the most common parameters to detect water quality impairment in rivers, lakes, etc. (Koparan, Koc, Privette, & Sawyer. 2018) and these sensors will be used to make the IoT enabled sonde. Floating gears will be installed on the drone to allow landing and take-off from the water surface. The data collected will be transmitted to the backend for analysis and visualization will be done in the form of the Eco-heart index developed by Sakai et al., (2018). This is useful especially for non-technical stakeholders and the raw parameters will also be available for scientists and researchers. To assess the accuracy of the sensors developed, it will be compared with laboratory analyzers using the paired t-test.

#### 1.1 Problem Statement

The effective functioning of inland aquatic bodies like lakes and ponds are being severely hindered by Eutrophication. This effect is on the rise due to rapid urbanization and other anthropogenic factors including farming, industrialization, etc. which is deteriorating the water quality on the surface and underground. (Taufiqurrahman, Tamami, Putra, & Harsono, 2017; Gafri et al., 2018). As a result, water resource management has become more important than ever (Siyang & Kerdcharoen, 2016).

Traditional laboratory testing methods to determine water quality, albeit accurate, are not ideal for early detection of contamination and lead to a slow response in an event of an emergency such as natural disasters. (Yang et al., 2018). Therefore, a timely informed decision can not be made with traditional methods of water sampling. (Siyang & Kerdcharoen, 2016; Zhu, Liu, Chen & Tian, 2018). Manual methods of water quality monitoring is expensive (Osborne, Hoffman, Lovelady, Holloway & Ferguson, 1981) and are prone to errors including sending samples back to the laboratory, error in data entry and retrieval, lack of calibration of laboratory equipment, error in data report, etc. (Chapman, 1996). Manual methods are also susceptible to human error and are not practical for continuous measurement which is essential for eliminating random errors or effects of isolated events. (Osborne, et al., 1981).

Water sampling (spatially separated and high frequency) is crucial in managing freshwater resources and maintaining public health. (Ore, Elbaum, Burgin & Detweiler, 2015) and real-time monitoring is required to detect the onset of algal blooms or contamination of water bodies in early stages (Dunbabin & Grinham, 2010; Saab, Shahrour, & Chehade, 2017). This real-time data collected using IoT can benefit water conservation management, policy-makers, etc. to take appropriate action. However, contemporary studies that demonstrate telemonitoring of water parameters using IoT are often expensive (Yang et al., 2018).

Another issue when it comes to conventional water quality monitoring is that the information is constrained within the practitioners and doesn’t help much when it comes to informing the general population (Indu & Choondal 2017). The data is published as Water Quality Index (WQI) which integrates all the measured parameters and hence individual parameters are lost. Also, the numerical value of WQI is not engaging or informative enough to the laymen community (Sakai et al., 2018).

#### 1.2 Significance of the Study

A cost-effective IoT enabled multiparameter probe mountable on an off-the-shelf UAV drone is proposed in this study. It has an accompanying backend for data analytics to communicate and visualize data in an easy manner to practitioners, and citizens alike. Firstly, it provides automatic measurements that have many advantages compared to manual methods like structuring of data, repeatability, etc. Aerial sampling also lowers operational cost and are useful for inspecting lakes, rivers, etc. periodically after natural disasters. UAVs can also be operated with minimal training and gives rapid access to inaccessible and hostile environments. (Koparan, Koc, Privette, & Sawyer, 2019).

The high-resolution spatiotemporal data obtained from UAV assisted sampling helps policy-makers to measure the impact of the policies (Osborne et al., 1981; Detweiler et al., 2015). Drones also enable multi-parameter mapping of the water body in real-time with high accuracy to provide a spatial distribution map of measurements which solves the problem of unreliable measurements from low-cost devices (Indu & Choondal 2017). According to Gopavanitha and Nagaraju (2018), real-time water quality measurement is also potentially useful in the distribution system, industries, aquafarming, etc.

In summary, the proposed study has the potential to streamline water conservation management and has the following advantages:

1. Inexpensive water sampling
2. Fast and accurate water sampling
3. Cutting down the need for trained personnel for sampling.
4. Increasing safety by eliminating the usage of boats during sampling
5. Access to remote aquatic bodies
6. User-friendly and effective visualization of water quality parameters

#### 1.3 Scope and Limitations

The main technological limitations of a UAV is its flight time and payload capacity. Also, a trained pilot for the UAV will be required for carrying out the water sampling. The IoT water quality measuring sonde is also reliable on cellular networks for internet access and there are some water quality parameters that can not be measured on-site. There is a limitation on the number of parameters to be measured due to constraints in time and resources. Also, benchmarking with several other commercially available sondes and assessing the efficacy of the proposed system is outside the scope of this study.

### 2. Literature Review

Significant research was carried out in the past few years in order to improve water quality monitoring since there is no single solution to tackle the multifarious issues that come with water conservation management (Behmel, Damour, Ludwig, Rodriguez, 2016). With rapid urbanization, population growth, industrialization, and climate change, real-time monitoring and analysis will be crucial to streamline decision making and rapid action in response to pollution (Gafri et al., 2018). With this growing need, researchers aimed to optimize water quality monitoring programs by improving the sensors and employing various data collection methods both static (fixed-site monitoring) and dynamic (sensor attached to a mobile vehicle). Development on the sensor side and different monitoring methods are presented in the first and second sections of this review and UAV assisted monitoring is covered in the third section.

***Smart Water Quality Sensors***

GSM was used to inform water conservation management authorities by sending SMS is there was any abnormality in the reading in a study by Mo, Zhao & Chen (2012). Their system made automatic measurements of pH, Turbidity, Temperature, EC & DO and analyzed the data to determine and abnormalities. In another study, an automatic sampler was designed by Wiranto, Mambu, Hiskia, Hermida & Widodo (2015) that collect 20 ml of water samples whenever the value of Dissolved Oxygen (DO) or pH exceeds a certain programmed threshold. The parameters are measured using in situ probes and transmitted wirelessly using the XBee module to the control station where the parameters are graphically displayed.

A low-cost sensor that measures four parameters was designed by Indu & Choondal (2017) which measured pH, Total Dissolved Solids (TDS), EC and Temperature electronically. The sensor was fairly accurate and could be developed under $60 without any IoT capabilities. Also, Taufiqurrahman, Tamami, Putra, & Harsono (2017) developed wireless sensors that measure temperature, TDS, Turbidity, and pH of potable water and transmits the data wirelessly using XBee module to a local control unit that determines the quality of the water using fuzzy logic but has no IoT features as well.

Smart sensors for water distribution networks (S::CAN and Eventlab) were evaluated by Saab, Shahrour, & Chehade, (2017) and they concluded that smart sensors are as effective as laboratory tests of water samples. For testing potable water, Gopavanitha and Nagaraju (2018) developed smart sensors that can measure physicochemical properties like Temperature, Turbidity, Electrical Conductivity (EC), pH and flow in real-time. The system used a Raspberry Pi module and the data was relayed to the backend for further analysis.

***Distributed Water Quality Sensor Network***

Vaddadi, Sadistap, & Kumar, (2012) also developed water quality sensors for potable water measuring DO, pH, temperature, EC and the sensors were deployed on a floating platform anchored to a fixed location. Several of these solar-powered floating sensors distributed across a water body measured and transmitted data to the central unit wirelessly through ZigBee from where the data was uploaded to the cloud to enable remote monitoring.

Another grid-based distributed surface water measurement was proposed by Konyha, (2016) which can forecast the spread of contamination in rivers or lakes. Five solar-powered monitoring stations with submersible sensors were deployed in this study to measure the water quality and the stations communicated with the communication column. The communication column communicates with the server via GPRS. The sensors measured Oxidation Reduction Potential (ORP), pH, EC, Temperature, DO, Nitrate ions and Chloride ions.

Solar-powered IoT enabled Mobile Sensor Nodes (MSN) were deployed to monitor Temperature, pH, DO, EC & ORP in the study conducted by Li, Xia, Chen, Zhao, & de Silva (2017). It provided high-resolution spatiotemporal data surface water quality which is useful for monitoring large water bodies. The MSN communicated with the base station wirelessly and the base station which then uploads the data to the server for further analysis using GPRS/3G/4G. The MSN also followed specified trajectories determined by the path planning algorithm to collect data across the water body.

***Underwater Robots for Water Quality Sampling***

Osborne, Hoffman, Lovelady, Holloway & Ferguson, (1981) proposed a submersible buoy capable of in situ water quality measurement (Temperature, Turbidity, pressure, EC, pH, ORP, DO and Fluoride) and transmitted data to the ground control station via an underwater communication channel. In a similar study by Park, Sohn, Kim, & Park, (2013), the effectiveness of water quality sensors (Turbidity, Temperature, pH, DO & EC) were realized that can be deployed to buoys and underwater robots The studies concluded that automatic measurements have a lot of advantages including fast and reliable data over manual methods.

An underwater robot dolphin was developed by Liu, Wu, & Yu (2016) with an on-board water quality sensing probe and demonstrated the feasibility of automatic water quality monitoring. Also, Hidalgo, Mendoza, & Cuellar, (2016) measured underwater parameters like Salinity, Turbidity, EC, pH, DO and Depth using probes mounted on a Remotely Operated Vehicle (ROV).

In a study by Xu, Gu, Li, Shi & Shen (2013), a multiparameter water quality probe was developed for underwater robots and the accuracy was benchmarked against XZ-001 and 5B-3B water quality analyzers. In a similar study, an underwater robot equipped with a multiprobe water quality sensor measured water quality and tagged it with to their respective latitude and longitudinal values. The underwater robot floats to the surface of the water to communicate with the control station on the ground to send the measured parameters. Experimental results demonstrated errors of the measurement were within 5% when compared to the lab water analyzers. Both the studies measured the underwater parameters like Temperature, Turbidity, Blue/Green Algae, Chlorophyll A, DO, pH & ORP

***Unmanned Surface Vehicle (USV) Water Quality Sampling***

Siyang & Kerdcharoen, (2016) mounted water quality sensors on a USV to make it mobile and take measurements from different locations to overcome the constraints of a fixed-location sensor. The sensors were manufactured by Atlas Scientific and the data (Temperature, pH, DO, ORP and EC) were obtained in real-time from the ground station which communicated with the sensor onboard the USV wirelessly via the XBee module. The ground station uploads the data to the internet from where the data is accessible from any location. In a similar study, ARK sensor buoy by AQUAS was carried by a UAV developed by Yang et al., (2018) which was used to measure Temperature, Turbidity, pH, EC, DO, Chlorophyll A & Potassium Ion. The buoy communicated with the computer in the ground station via Bluetooth and uploaded the measured data to the cloud using a 4G network.

To assess the quality of freshwater in lakes and rivers, a fleet of autonomous Robot Sensing Boats (RSB) was implemented to monitor water quality parameters (Temperature, pH & DO) that were sent to the server in real-time by the RSBs. They conducted in situ water quality assessments using a multiparameter sonde and experimented in fresh and algae-laden water for over three months to prove the proposed telesupervision architecture. The RSBs navigated using an architecture named Multilevel Autonomy Telesupervison Architecture (MARTA) developed for water quality sampling tasks. Another automatic cruise system for water sampling was proposed by Zhu, Liu, Chen & Tian. (2018). The ship mounted with a multiparameter water quality sonde that measured DO, pH, Temperature and Ammonia-Nitrogen in real-time while navigating autonomously to widen the range of measurements. The remote monitoring and control were assisted by an Android app they developed for this study.

Autonomous catamaran type boats were also quite popular when it came to automatic water sampling due to their stability of sailing. Koprowski et al., (2013) used an autonomous boat to measure the physicochemical properties of drinking water and also used to measure fish density using the fish’s spatial location. The robot followed a designated path to measure the parameters and allowed remote monitoring and saved the data locally. Dunbabin & Grinham, (2010) also used a solar-powered autonomous catamaran and experimentally evaluated the capabilities of monitoring water quality parameters such as Temperature, EC, DO and Chlorophyll using YSI Sonde. The catamaran was also referred to as Autonomous Surface Vehicles (ASV) and was capable of navigating complex environments and continuously monitoring the water parameters in real-time. The collected data is relayed back to the shore-based facility for further analysis. They also proved the efficacy of the remote water profiling as it was strongly correlated with the manual methods.

***Unmanned Aerial Vehicle (UAV) Water Quality Sampling***

In order to conduct in situ water quality measurement, a hexacopter was equipped with floatation gears and water quality acquisition probes (Temperature, EC, DO & pH) in the research conducted by Koparan, Koc, Privette, & Sawyer, (2018). The UAV allowed multipoint sensing to cover a wide area accurately with the error staying below 4%. The floatation equipment allowed landing and take-off from the surface of the water and the water parameter data was stored locally in an SD card. In a later study by Koparan et al., (2019), three cartridges were used to sample water at different depths along with the in-situ measurements of the previous parameters. Their research concluded that UAVs lower operational and logistics cost and allows quick access to inaccessible and hostile environments with flight time being the only bottleneck.

Similarly, a hybrid of a UAV and a hovercraft was designed for water quality monitoring in this study by Esakki et al., (2018) which had a payload capacity of 7 kg. This allowed the amphibious vehicle to collect 500ml of water samples from water bodies using a pump and containers. Moreover, the UAV was also equipped with water quality acquisition probes for Turbidity, pH, DO & EC that were IoT enabled allowing the data to be uploaded in the cloud using a wifi hotspot. In another study by Shunmuga Perumal, Samson Arun Raj, Bharathi, Mohan Raju, & Yogeswari, (2017) a LIDAR was attached to the drone to measure water level and capacity which is relayed to the ground control station wirelessly. The control station is also connected to stationary water quality sensors and rainfall sensors installed in the water reservoir. The control station collects and processes the data and transforms it into a knowledge base.

Detweiler et al., (2015) installed a pump and cartridges on the drone that samples water from different remote locations and brings back water samples for laboratory testing. They found that water quality parameters obtained from aerial sampling correlate with the conventional manual sampling methods. Given the good accuracies of the water quality parameters from aerial sampling, Ore, Elbaum, Burgin & Detweiler (2015) also found that UAV sampling provides high-resolution spatiotemporal data quickly while cutting down labor and cost.

From this literature review, it was observed that smart sensors have allowed in situ measurement of water quality parameters and it has also been proven to be as effective as laboratory tests. These sensors deployed in a large number in static stations are able to provide high-resolution spatiotemporal data about the quality of water in the water bodies. The sensors can also be attached to an underwater robot, USV or UAV to collect data from diverse spatial locations and it also gives access to remote and inaccessible areas in a fast and convenient way. These various methods were also proven to be closely related to the standards of traditional sampling methods. However, there are certain limitations in these solutions that are still preventing the solution to be ubiquitous and widely used by the water conservation community.

Firstly, most of the research article failed to provide proper accuracy measurements and lacked robust comparison with standard laboratory devices for the low-cost sensors that were developed. Moreover, the cost to develop the sensors and the calibration strategies involved were not addressed. Many of these standalone sensors stored the data locally in their control station and data was not uploaded to the cloud. Also, the stationary sensors require periodical maintenance which is again arduous and costly (Xu et al., 2013). Secondly, the distributed sensor networks deployed sensors that are expensive and deploying it in large numbers to cover a large water body becomes very costly. Also, many of the standalone sensors and distributed sensors communicated with a central control station. Implementation of this architecture is also expensive and time-consuming.

For underwater robots, one of the main challenges is underwater communication and hence there is always a significant delay in the measurement of the parameters and sending the data as the robot has to come to the surface of the water to transmit data. As mentioned in the literature, the distance between the robot and the remote control station and the communication delay are the major bottlenecks (Xu et al., 2013). Also, most of the underwater robots and USV used industrial-grade sonde which is expensive and mostly lacks IoT capabilities.

So far in the literature, UAV drones that were used to collect water samples from water bodies proved to be effective. However, the in situ water quality acquisition probe that was used to collect the data were stored in local storage and was not available online. Shunmuga Perumal et al., (2017) however, implemented IoT enabled low-cost sensor but it lacked robust analysis and comparison of the accuracy of the sensors.

Lally, O’Connor, Jensen, & Graham, (2019) stated in their paper that one of the key limitations of UAV drone water sampling is sampling payloads, legal restrictions, etc. and a thorough cost-benefit analysis is required before the drone can be useful in monitoring water quality. However, with recent advancements in drone technology has shown immense potential in water sampling according to their research and also suggested the use of real-time water quality sensors. Drone sampling has also proven to reduce cost and effort(Ore, Elbaum, Burgin & Detweiler, 2015; Koparan, Koc, Privette, & Sawyer, 2019). Hence installing IoT enabled low-cost sensors to an off-the-shelf drone with accompanying data analysis and visualization is an interesting area to explore.

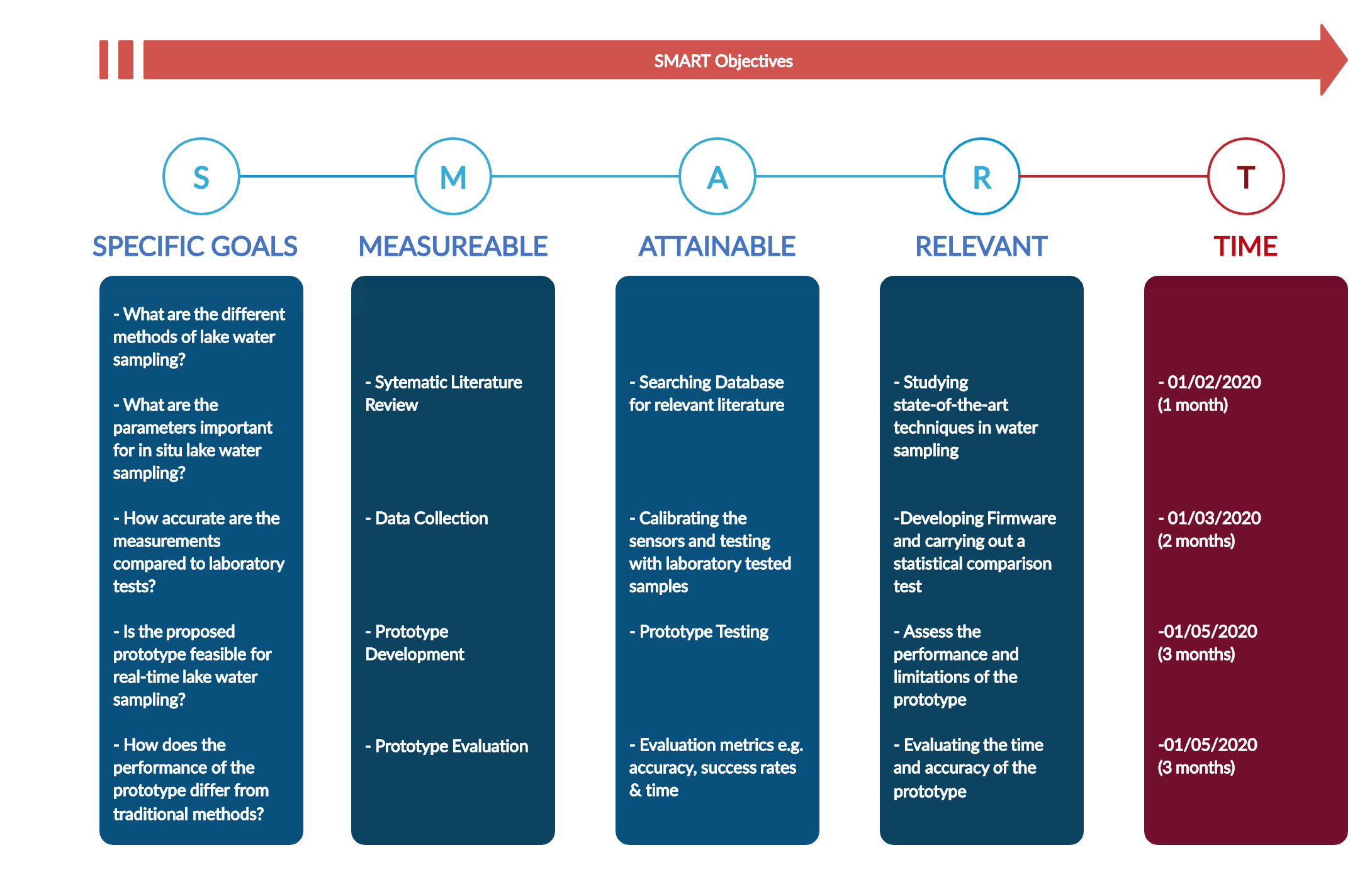
### 3. Methodology

Table 3.1 shows the mapping of the research methodology and Figure 3.1 shows the graphical representation of the SMART methodology. The study commences with a literature search and systematic review to identify discriminators before the development of the proposed prototype. The water quality sensors are then calibrated and benchmarked with laboratory equipment for all the parameters (Temp, EC, DO and pH). The multiparameter sonde and floatation gears will be mounted on an off-the-shelf UAV-drone. After the integration, functionality testing will be carried at the Tasik Varsity, UM where results taken by prototype will be compared against conventional sampling techniques to evaluate the performance of our prototype.

**Table 3.1: Mapping of RQ, RO, Methodology, and Outcome**

| **Research Questions** | **Research Objectives** | **Methodology** | **Outcome** |
| --- | --- | --- | --- |
| What are the various methods used for lake water sampling? | To study appropriate discriminators in distinguishing different monitoring methods and parameters for efficient lake water sampling. | a) Literature search  b) Systematic literature review | a) Findings on the performance of existing approaches  b) Core parameters for water quality monitoring |
| What are the parameters important for in situ water sampling? |
| How accurate are the in situ measurements compared to laboratory equipment? | To compare the sensor data with laboratory measurements | a) Proof-of-concept  b) Calibration of sensors  c) Data collection from lab equipment  d) Comparison test | a) Custom-built IoT-enabled sensor.  b) Develop firmware and integrate with the backend  c) Calibrate the Sensor  d) Visualize the data on the backend |
| Is the proposed prototype a feasible solution for a real-time lake water sampling? | To test the performance of the proposed prototype in real-time | a) Development and integration of the sensor with the drone  b) Validating and fine-tuning | 1. New findings on the proposed prototype in terms of time and accuracy |
| How does the performance of the proposed prototype differ from standard methods? | To evaluate and compare the performance of the proposed prototype with standard methods of measurement | a) Comparative evaluation | a) Results of performance comparison with existing solutions |

**Fig 3.1: SMART Research Methodology**



### References

Al-Badaii, F., Shuhaimi-Othman, M., & Gasim, M. B. (2013). Water quality assessment of the Semenyih river, Selangor, Malaysia. Journal of chemistry, 2013.

Azizul, Z. H. (2019). Internal discussion with SPAN and NAHRIM on challenges of lake sampling in Malaysia. Unpublished manuscript.

Behmel, S., Damour, M., Ludwig, R., & Rodriguez, M. J. (2016). Water quality monitoring strategies — A review and future perspectives. Science of the Total Environment, 571, 1312–1329. <https://doi.org/10.1016/j.scitotenv.2016.06.235>

Beloev, I. H. (2016). A review on current and emerging application possibilities for unmanned aerial vehicles. Acta technological agricultural, 19(3), 70-76.

Chapman, D. (1996). Water Quality Assessments—A Guide to Use of Biota, Sediments and Water in Environmental Monitoring, Cambridge University Press, Cambridge

Detweiler, C., Ore, J. P., Anthony, D., Elbaum, S., Burgin, A., & Lorenz, A. (2015). Environmental Reviews and Case Studies: Bringing Unmanned Aerial Systems Closer to the Environment. Environmental Practice, 17(3), 188–200. <https://doi.org/10.1017/S1466046615000174>

Dunbabin, M., & Grinham, A. (2010). Experimental evaluation of an autonomous surface vehicle for water quality and greenhouse gas emission monitoring. Proceedings - IEEE International Conference on Robotics and Automation, 5268–5274. <https://doi.org/10.1109/ROBOT.2010.5509187>

Esakki, B., Ganesan, S., Mathiyazhagan, S., Ramasubramanian, K., Gnanasekaran, B., & Son, B. et al. (2018). Design of Amphibious Vehicle for Unmanned Mission in Water Quality Monitoring Using Internet of Things. *Sensors*, *18*(10), 3318. doi: 10.3390/s18103318

Gafri, H., Zuki, F., Zeeda, F., Affan, N., Sulaiman, A., & Norasiah, S. (2018). A Study on Water Quality Status of Varsity Lake and Pantai River, Anak Air Batu River in UM Kuala Lumpur, Malaysia and Classify it based on (WQI) Malaysia. International Journal of Environmental Quality, Vol. 29, pp. 51–65. <https://doi.org/10.6092/issn.2281-4485/7967>

Gopavanitha, K., & Nagaraju, S. (2018). A low cost system for real time water quality monitoring and controlling using IoT. 2017 International Conference on Energy, Communication, Data Analytics and Soft Computing, ICECDS 2017, 3227–3229. <https://doi.org/10.1109/ICECDS.2017.8390054>

Hidalgo, F., Mendoza, J., & Cuellar, F. (2016). ROV-based acquisition system for water quality measuring. OCEANS 2015 - MTS/IEEE Washington, 1–5. <https://doi.org/10.23919/oceans.2015.7404435>

Hongmin, G., Hui, G., Chenming, L., Junlin, Q., & Lizhong, X. (2013). Water quality data measurement and analysis system equipped in underwater navigation robot. Sensors and Transducers, 155(8), 128–135.

Siregar, M. (2004). On-line water quality monitoring on Brantas river East Java Indonesia. *2004 IEEE International Conference On Semiconductor Electronics*. doi: 10.1109/smelec.2004.1620825

Indu, K., & Choondal, J. J. (2017). Modeling, development & analysis of low cost device for water quality testing. 2016 IEEE Annual India Conference, INDICON 2016, 1–6. <https://doi.org/10.1109/INDICON.2016.7839131>

Konyha, J. (2016). Grid-based wide area water quality measurement system for surface water. Proceedings of the 2016 17th International Carpathian Control Conference, ICCC 2016, 341–344. <https://doi.org/10.1109/CarpathianCC.2016.7501120>

Koparan, C., Koc, A. B., Privette, C. V., & Sawyer, C. B. (2018). In situ water quality measurements using an unmanned aerial vehicle (UAV) system. Water (Switzerland), 10(3). <https://doi.org/10.3390/w10030264>

Koparan, C., Koc, A. B., Privette, C. V., & Sawyer, C. B. (2019). Autonomous in situ measurements of noncontaminant water quality indicators and sample collection with a UAV. Water (Switzerland), 11(3). <https://doi.org/10.3390/w11030604>

Koprowski, R., Wróbel, Z., Kleszcz, A., Wilczyński, S., Woźnica, A., & Łozowski, B. et al. (2013). Mobile sailing robot for automatic estimation of fish density and monitoring water quality. *Biomedical Engineering Online*, *12*(1), 60. doi: 10.1186/1475-925x-12-60

Lally, H. T., O’Connor, I., Jensen, O. P., & Graham, C. T. (2019). Can drones be used to conduct water sampling in aquatic environments? A review. Science of the Total Environment, 670, 569–575. <https://doi.org/10.1016/j.scitotenv.2019.03.252>

Li, T., Xia, M., Chen, J., Zhao, Y., & de Silva, C. (2017). Automated water quality survey and evaluation using an IoT platform with mobile sensor nodes. Sensors (Switzerland), 17(8). <https://doi.org/10.3390/s17081735>

Linchant, J., Lisein, J., Semeki, J., Lejeune, P., & Vermeulen, C. (2015). Are unmanned aircraft systems (UAS s) the future of wildlife monitoring? A review of accomplishments and challenges. Mammal Review, 45(4), 239-252.

Liu, J., Wu, Z., & Yu, J. (2016). Design and implementation of a robotic dolphin for water quality monitoring. 2016 IEEE International Conference on Robotics and Biomimetics, ROBIO 2016, 835–840. <https://doi.org/10.1109/ROBIO.2016.7866427>

Mo, D., Zhao, Y., & Chen, S. (2012). Automatic measurement and reporting system of water quality based on GSM. Proceedings - 2012 International Conference on Intelligent Systems Design and Engineering Applications, ISDEA 2012, 1007–1010. <https://doi.org/10.1109/ISdea.2012.595>

Mooney, J. G., & Johnson, E. N. (2014). A Comparison of Automatic Nap-of-the-earth Guidance Strategies for Helicopters. Journal of Field Robotics, 32(8), 1–17. https://doi.org/10.1002/rob

Nilsson, C. (2009). Reservoirs. Encyclopedia of Inland Waters, 625–633. <https://doi.org/10.1016/B978-012370626-3.00039-9>

NAHRIM. 2009. Study on the Status of Eutrophication of Lakes in Malaysia. NAHRIM, Seri Kembangan.

Nishar, A., Richards, S., Breen, D., Robertson, J., & Breen, B. (2016). Thermal infrared imaging of geothermal environments and by an unmanned aerial vehicle (UAV): A case study of the Wairakei–Tauhara geothermal field, Taupo, New Zealand. Renewable Energy, 86, 1256-1264.

Ore, J., Elbaum, S., Burgin, A., & Detweiler, C. (2015). Autonomous Aerial Water Sampling. Journal Of Field Robotics, 32(8), 1095-1113. doi: 10.1002/rob.21591

Osborne, P., Hoffman, E., Lovelady, R., Holloway, R., & Ferguson, R. (1981). A Water Quality Monitoring Robot. *OCEANS 81*. doi: 10.1109/oceans.1981.1151651

Park, J., Sohn, J., Kim, S., & Park, J. (2013). Design and field testing of water quality sensor modules designed for round-the-clock operations from buoys and biomimetic underwater robots. Studies in Computational Intelligence, Vol. 466, pp. 209–216. <https://doi.org/10.1007/978-3-642-35485-4_16>

Podnar, G., Dolan, J. M., Low, K. H., & Elfes, A. (2010). Telesupervised remote surface water quality sensing. IEEE Aerospace Conference Proceedings, (Figure 1), 1–9. <https://doi.org/10.1109/AERO.2010.5446668>

Saab, C., Shahrour, I., & Chehade, F. H. (2017). Smart technology for water quality control: Feedback about use of water quality sensors. 2017 Sensors Networks Smart and Emerging Technologies, SENSET 2017, 2017-Janua, 1–4. <https://doi.org/10.1109/SENSET.2017.8125060>

Sakai, N., Mohamad, Z. F., Nasaruddin, A., Abd Kadir, S. N., Mohd Salleh, M. S. A., & Sulaiman, A. H. (2018). Eco-Heart Index as a tool for community-based water quality monitoring and assessment. Ecological Indicators, 91(March), 38–46. <https://doi.org/10.1016/j.ecolind.2018.03.079>

Sharip, Z., & Suratman, S. (2017). Formulating Specific Water Quality Criteria for Lakes: A Malaysian Perspective. In Water Quality. InTech.

Shunmuga Perumal, P., Samson Arun Raj, A., Bharathi, B. M. S., Mohan Raju, G., & Yogeswari, K. (2017). UAV assisted automated remote monitoring and control system for smart water bodies. Proceedings - 2017 2nd International Conference on Recent Trends and Challenges in Computational Models, ICRTCCM 2017, 116–120. <https://doi.org/10.1109/ICRTCCM.2017.85>

Siyang, S., & Kerdcharoen, T. (2016). Development of unmanned surface vehicle for smart water quality inspector. 2016 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, ECTI-CON 2016, 1–5. <https://doi.org/10.1109/ECTICon.2016.7561370>

Taufiqurrahman, Tamami, N., Putra, D. A., & Harsono, T. (2017). Smart sensor device for detection of water quality as anticipation of disaster environment pollution. Proceedings - 2016 International Electronics Symposium, IES 2016, 87–92. <https://doi.org/10.1109/ELECSYM.2016.7860981>

Turner, I. L., Harley, M. D., & Drummond, C. D. (2016). UAVs for coastal surveying. Coastal Engineering, 114, 19-24.

Vaddadi, S. K., Sadistap, S. S., & Kumar, P. (2012). Development of embedded wireless network and water quality measurement systems for aquaculture. Proceedings of the International Conference on Sensing Technology, ICST, 637–641. <https://doi.org/10.1109/ICSensT.2012.6461757>

Wiranto, G., Mambu, G. A., Hiskia, Hermida, I. D. P., & Widodo, S. (2015). Design of online data measurement and automatic sampling system for continuous water quality monitoring. 2015 IEEE International Conference on Mechatronics and Automation, ICMA 2015, 2331–2335. <https://doi.org/10.1109/ICMA.2015.7237850>

Xu, L., Gu, H., Li, C., Shi, A., & Shen, J. (2013). System design of water quality monitoring robot with automatic navigation and self-test capability. International Journal of Control and Automation, 6(5), 67–82. <https://doi.org/10.14257/ijca.2013.6.5.07>

Yang, T., Hsiung, S., Kuo, C., Tsai, Y., Peng, K., & Peng, K. et al. (2018). Development of unmanned surface vehicle for water quality monitoring and measurement. 2018 IEEE International Conference On Applied System Invention (ICASI). doi: 10.1109/icasi.2018.8394316

Zhu, C., Liu, X., Chen, H., & Tian, X. (2018). Automatic cruise system for water quality monitoring. International Journal of Agricultural and Biological Engineering, 11(4), 220–228. <https://doi.org/10.25165/j.ijabe.20181104.2658>