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Water Quality Monitoring and Pollution Control Technologies

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ABSTRACT: The rapid urbanization and industrial development have resulted in water contamination and water quality deterioration at an alarming rate, deeming its quick, inexpensive and accurate detection imperative. Conventional methods to measure water quality are lengthy, expensive and inefficient, including the manual analysis process carried out in a laboratory. The research work in this paper focuses on the problem from various perspectives, including the traditional methods of determining water quality to gain insight into the problem and the analysis of state-of-the-art technologies, including Internet of Things (IoT) and machine learning techniques to address water quality. After analyzing the currently available solutions, this paper proposes an IoT-based low-cost system employing machine learning techniques to monitor water quality in real time, analyze water quality trends and detect anomalous events such as intentional contamination of water.

KEYWORDS: water quality, monitoring, pollution, control, technologies

I. INTRODUCTION

There are many ways to monitor water conditions. Monitoring specialists sample the chemical condition of water, sediments, and fish tissue to determine levels of key constituents such as dissolved oxygen, nutrients, metals, oils, and pesticides. They also monitor physical conditions such as temperature, flow, sediments, and the erosion potential of stream banks and lake shores. Biological measurements of the abundance and variety of aquatic plant and animal life and the ability of test organisms to survive in sample water are also widely used to monitor water conditions.[1,2,3]

Monitoring can be conducted at regular sites ("fixed stations") on a continuous basis; at selected sites on an as-needed basis, to answer specific questions, or to characterize a watershed; on a temporary or seasonal basis (for example, during the summer at bathing beaches); at random sites throughout an area or state; or on an emergency basis (such as after a spill). Increasingly, monitoring efforts are aimed at determining the condition of entire watersheds -- the area drained by rivers, lakes, and estuaries. This is because we have come to realize the impact of land-based activities on the waters that drain the land, and the interconnectedness of all types of waterbodies, including those beneath the ground.

Why monitor?

Monitoring can be conducted for many purposes. Five major purposes are to:

- characterize waters and identify changes or trends in water quality over time;
- identify specific existing or emerging water quality problems;
- gather information to design specific pollution prevention or remediation programs;
- determine whether program goals -- such as compliance with pollution regulations or implementation of effective pollution control actions -- are being met; and

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- respond to emergencies, such as spills and floods.

Some types of monitoring activities meet several of these purposes at once; others are specifically designed for one reason.

Who monitors?[4,5,6]

The responsibility to monitor water quality rests with many different agencies. State pollution control agencies and Indian tribes have key monitoring responsibilities and conduct vigorous monitoring programs. They receive pollution control and environmental management grants from the U.S. Environmental Protection Agency (EPA) that help them establish and maintain monitoring programs and report the results of monitoring activities to the EPA. Interstate commissions, like states and tribes, may also receive grants and maintain monitoring programs. Many local governments, such as city and county environmental offices, also conduct water quality monitoring within their boundaries. The EPA helps administer grants for water quality monitoring and provides technical guidance on how to monitor and how to report monitoring results.

The EPA also conducts some limited monitoring of its own. Its Environmental Monitoring and Assessment Program (EMAP) managed by the Office of Research and Development, is designed to provide status and trends information on statistically selected waters representing a variety of ecosystems. EPA Regional Offices conduct compliance and inspection monitoring of wastewater discharged by industries and municipal treatment facilities. EPA Headquarters and Regional Offices also sponsor or conduct monitoring projects designed to answer specific questions. EPA and state and tribal partners are currently working together on a series of statistically-designed surveys of the nation´s waters that will for the first time provide valid data on water quality trends and key stressors. Information on these studies are available on our National Aquatic Resource Surveys homepage.

Other Federal agencies are also involved in water quality monitoring. The U.S. Geological Survey (USGS) conducts extensive chemical monitoring through its National Stream Quality Accounting Network (NASQAN) at fixed locations on large rivers around the country.[7,8,9] Its National Water Quality Assessment Program (NAWQA) uses a regional focus to study status and trends in water, sediment, and biota. The U.S. Fish and Wildlife Service, the National Oceanic and Atmospheric Administration, the U.S. Army Corps of Engineers, and the Tennessee Valley Authority are other examples of Federal agencies that conduct water quality monitoring to support their programs and activities.

Lastly, private entities such as universities, watershed associations, environmental groups, and permitted dischargers also conduct water quality monitoring. They may collect water quality data for their own purposes, or to share with government decision makers. Volunteer monitors -- private citizens who volunteer to be trained in monitoring methods, regularly collect and analyze water samples, conduct visual assessments of physical conditions, and measure the biological health of waters -- are a rapidly growing contingent providing increasingly important environmental information. Volunteer monitoring data are used for local decision-making and often to supplement state water quality data. For more information on volunteer monitoring, visit our volunteer monitoring website.

What happens to monitoring data?

Data collected by state, local and federal agencies and private entities are needed to build the assessments we need to make better pollution control decisions. Without data, we simply cannot know where pollution problems exist, where we need to focus our pollution control energies, or where we've made progress.

Many agencies and organizations maintain computerized data systems to store and manage the water quality data they or others collect. One of the largest such ambient water quality data system is EPA´s STORET (for STOrage and RETrieval) system. Data collected by state, local and federal agencies and some private entities such as universities and volunteer monitors are entered into STORET. Raw data in STORET can be accessed, analyzed, and summarized by many users and for many purposes.

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STORET is evolving to keep pace with developing technologies; in the near future, it will become easier to use and more responsive to user capabilities and needs. The next generation of STORET, known as WQX (for Water Quality eXchange), will provide much more flexibility to users while retaining standard data elements that provide consistency and quality control.

States and tribes turn their data into information about whether their waters meet water quality standards. States report his information to EPA every two years under Section 305(b) of the Clean Water Act. EPA, in turn, summarizes these state water quality assessment reports into a national Report to Congress called the National Water Quality Inventory. This report now includes a database of state-by-state assessment information that can[10,11,12] be viewed down to the waterbody level. Visit our Section 305(b) website for the latest available information reported by the states on the quality of their assessed waters.

The Future of Water Quality Monitoring

This brief introduction has provided a glimpse into the complex world of water quality monitoring. Efforts are currently underway to improve how monitoring is conducted, how information is shared, and how decisions based on monitoring are made.

In response to EPA guidance, states have prepared comprehensive, long-term monitoring strategies that address all water types, including those such as wetlands for which little data currently exist. These strategies will help identify needed actions and overall challenges facing states as they work to improve monitoring over the coming decade.

The states and EPA are taking steps toward streamlining and improving water quality monitoring and assessment by integrating monitoring and r eporting requirements under Sections 305(b) and 303(d) of the Clean Water Act. (Under Section 303(d), states, territories, and authorized tribes are required to develop lists of impaired waters.) EPA is also working toward improving electronic reporting of monitoring data to make it increasingly accessible to the public and to decision-makers at all levels of government.

National and state-level statistical surveys - designed using modern survey techniques in which random sites are sampled to reflect all waters that have similar ecological characteristics -- are providing a new, scientifically-valid baseline of information to help us evaluate the success of our national efforts to protect and restore water quality. These surveys also provide funding and expertise that will enhance each state´s ability to monitor and assess the quality of its waters in the future.

II. DISCUSSION

Water quality monitoring consists of frequent analysis of the main constituents. The required data input consists of: (1) mean composition of the influent; (2) mean composition of native groundwater in each layer of the target aquifer; (3) native geochemistry of each layer of the target aquifer; (4) the cumulative frequency curve of detention times in each model layer or flow path as derived from either separately run hydrological model or tracer breakthrough data; and (5) specific information derived from the mass balance of the water phase (the reactions that are needed, how O_2 and NO_3^- distribute over the various redox reactions, etc.).

The results demonstrate the following effects: (1) displacement of the native groundwater by the influent, including effects of dispersion; (2) leaching of reactive aquifer constituents: exchangeable cations[13,14,15], calcite, organic matter iron sulfides and MnO_2; and (3) breakdown of organic micropollutants.

With regard to chemical reactions, target aquifer samples have been determined to give information on grain size distribution and porosity, and quantitative chemical analysis for total element content (by X-ray fluorescence (XRF)), iron sulfides, calcium carbonate, exchangeable cations, organic matter, and organic carbon.

Monitoring water quality is very important for maintaining ecosystem health and the livelihood of the population. It reflects the health of surface water bodies as a snapshot in time (weeks, months, and years). Therefore, best practices

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and efforts are needed to monitor and improve water quality. As hyperspectral remote sensing can capture water quality parameters, it could be viable solution for water quality management. For example, Zhang et al. (2020) in their study, provided a self-adapting selection method in integration of artificial neural networks to quantitatively predict water quality parameters such as phosphorus, nitrogen, biochemical oxygen demand, chemical oxygen demand and chlorophyll a. Similarly for lake water quality, specific heavy metals were detected and predicted using portable FieldSpec_3 ASD spectroradiometer and various spectra were taken in the laboratory (Rostom et al., 2017). Studies by Shafique et al. (2003) used the hand-held spectrometer data and collected water spectrum from rivers directly. They established and used correlations between the ground-truth data and spectrum for developing spectral indices to estimate chlorophyll a, turbidity, and phosphorus. In other study (Sailaja et al., 2017), five water quality parameters (i.e. chlorophyll, turbidity, Secchi depth, total phosphorus, and total suspended solids) were estimated through regression models. They took field spectroradiometer and hyperion reflectance values and related these with in situ ground data.

Wang and Yang (2019) provided a quantitative systematic review to identify existing challenges and future directions. Their review identified that the semiempirical method was used by most of the researchers and is the most frequently used inversion method. They concluded that the ground object spectrometer is a highly applied data source and most of the study provided estimates of chlorophyll, suspended solid, and so forth, but rarely considered the human induced factors which is a drawback of the model's robustness.

Online water quality monitoring in drinking water distribution systems has helped drinking water utilities deliver safe and high-quality water to consumers for years. Traditionally, utilities have used online sensors for process control at the water treatment plant. For example, monitoring drinking water[16,17,18] quality parameters can help determine whether a sufficient disinfectant residual is present in the distribution system or it has degraded below regulatory limits at the system's far reaches. Additional information related to disinfection byproduct control is presented in Chapter 1.7. Additionally, utilities periodically implement new treatment technologies or upgrade old ones, and online water quality monitoring can help assess if treatment plant changes affect water quality in the distribution system. Finally, drinking water utilities must abide by regulatory requirements. Usually, online water quality data cannot replace grab samples that are analyzed in a laboratory for a specific analytes or regulatory compliance purposes. However, water quality data can alert an operator to a condition that may have an impact on a regulated contaminant or parameter.

After the events of 11 September 2001, the direction of online water quality monitoring research shifted to infrastructure security applications. Motivation for the focus on security came from Homeland Security Presidential Directives (HSPDs). HSPD-7 was established in December 2003 and directed federal department agencies to 'identify and prioritize critical infrastructure and to protect them from terrorist attacks' (Department of Homeland Security (DHS), 2003). HSPD-7 established the Environmental Protection Agency (EPA) as the lead agency for drinking water and wastewater security in the US. Drinking water and wastewater were included in the scope of HSPD-9, which was published in January 2004 and 'established a national policy to defend the agriculture and food system against terrorist attacks, major disasters, and other emergencies' (Department of Homeland Security (DHS), 2004).[19,20,21]

Defending the water supply from emergencies or terrorist attacks requires development of a comprehensive monitoring and detection system that provides early detection capability. In response to HSPD-9, EPA developed the Water Security Initiative (WSi), which focuses on the implementation of multifaceted drinking water contamination warning systems (CWSs) that combine enhanced physical security monitoring, consumer complaint surveillance, public health monitoring, sampling and analysis, and online water quality monitoring (USEPA, 2005a, b). EPA's National Homeland Security Research Center has conducted extensive research to support the online water quality monitoring facet of the WSi.

The first part of this chapter focuses on reporting data and discussing insights gained from online water quality monitoring research performed at USEPA's Test and Evaluation (T&E) facility. The second part focuses on data analysis with commercially available event detection algorithms and the challenges associated with data analysis. The third part discusses operation and maintenance (O&M) of sensors in the field and how this may affect sensor selection in a CWS. Finally, the authors' insights on the future direction of online water quality monitoring in the field and where research will likely be focused are discussed.

III. RESULTS

Drinking water quality monitoring involves a wide range of water quality assessments encompassing the entire water supply system. Careful consideration should be given to the water quality characteristics to be analyzed, including

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sampling location and frequency, analytical method, recording, evaluation, and reporting, with the emphasis on putting more effort into understanding the entire water supply system. Monitoring can be separated into two categories, operational monitoring and performance monitoring. Effective operational monitoring is critical for confirming that individual barriers for controlling hazards are functioning properly and effectively. Data from operational monitoring are used as triggers for immediate short-term preventive and corrective actions to operational processes to maintain drinking water quality. Performance monitoring includes[22,23,24] regular sampling and testing to demonstrate conformance with guideline values and other regulatory requirements.

Traditionally, water quality monitoring relies on multi-taxon indices, such as the Biological Monitoring Working Party (BMWP) (Hawkes, 1997) and an adaptation of that method, the South African Scoring System version 5 (SASS5) (Dickens and Graham, 2002). The advantage of multi-taxon indices is that they are relatively rapid assessments, as they usually operate at a coarse taxonomic resolution (family-level). The indices include multiple functional feeding groups, which have different tolerances to stressors. These advantages also lead to significant limitations. In the multi-taxon scoring system, sensitivity to pollution scores are set at the family level, and taxa identified to the family level. This ignores taxonomic and ecological sensitivities to stress at the taxonomic genus and species levels that make up a family. Secondly, these methods do not account for the sensitivity of individual functional feeding groups (e.g., shredders which feed of leaf litter, grazers which feed on periphyton, or predators which in turn feed on the grazers and shredders and other predators). An alternative, therefore, might be to use a single-taxon assessment method instead. The next section focusses on the use of a group of invertebrate predators in rivers and wetlands (dragonflies), but there are some notable uses of single-taxon approaches, for example using Chironomidae (Nicacio and Juen, 2015) in other habitat types including lakes.

An integrated water quality monitoring device placed in a backpack was designed for the quick measurement of several parameters thanks to a multiparameter probe, and an innovative UV sensor. On the station chosen, the water to be analyzed is pumped into the device using a sampling tube integrating a pump immersed in the watercourse. The multiparameter probe allows the direct measurement of the electrical conductivity, temperature, pH, oxidation–reduction potential, turbidity, and oxygen content of the water sampled. The water is then analyzed using a double optical path UV–visible spectrophotometer adapted to different concentration levels. Nitrate and DOC concentrations can be easily determined [42].

After results displayed on smartphone screen, within 1 minute, the water is discharged. This system was validated during a research project [43] that was conducted for 1 year (September 2018–December 2019) for the identification of nitrate emission and abatement zones at a fine spatial resolution, by measuring water quality every 50 to 100 m in the watersheds of the Bay of Douarnenez and the Lieue de Grève (Brittany, France). The portable measurement was validated from water samples and lab analysis. The adjustment was excellent with a determination coefficient of 0.99 and 0.95 for nitrate and Dissolved Organic Carbon (DOC), respectively (for more than 200 samples). Furthermore, the qualitative analysis of evolution of spectra along the river continuum, including all tributaries, drains, ditches, plant rejects, and other point sources observed in the field is a powerful tool to interpret hydrology and anthropic impacts in watersheds, complementary to all well-known parameters measured. The designed procedure makes it possible to increase the number of subwatersheds that can be monitored in the same day, and to increase the resolution of the measurement networks from one point per several tens or hundreds of km^2 to one point per subwatershed of a few km^2. High spatial resolution measurement allows the localization of highly charged groundwater resurgences and the identification of potential sites for the development of buffer zones. In all contexts, measurement at high spatial resolution allows a better understanding of the functioning of a watershed and the nature of the flows in space, and thus time, that structure the watershed. It also allows the definition of strategies for the implementation of agri-environmental measures within green algae control plans and the nature of a temporal monitoring network.

Besides UV–visible spectrophotometry, handheld fluorometer was also proposed by Chen et al. [44]. A field, lightweight laser fluorometer based on the method of laser-induced fluorescence was developed for water quality monitoring. The hyperspectral LIF technique has the potential to simultaneously detect multiple water quality parameters of interest, which is particularly advantageous in optically complex waters. Under the laser excitation at 405 nm, the peak near 685 nm in the emission spectra corresponds to chlorophyll-a, the peak nearby 470 nm corresponds to Raman scattering (also linked to TSM response), and the peak near 508 nm corresponds to CDOM constituent. Simultaneous estimates of chlorophyll-a, CDOM, and TSM measured by the laser fluorometer were observed to agree well with those measured by laboratory methods after sampling, (R^2>0.85) in Hangzhou Bay water (China). This procedure allowed successful high-resolution and high-frequency monitoring in a complex estuarine system.

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Before considering WQ monitoring (WQM), it is interesting to examine how people perceive WQ through the visual aspect of water. The visual perception is, by definition, linked to the visible region of light, between violet (around 400 nm) and red (700 nm). Thus color and clarity–transparency are the usual criteria for human perception of WQ [3]. A recent study involving 167 participants reported on the perception of 26 photographs taken under water in a recreational river (with flow sufficient for canoe practice), a few days after rainfall [4]. At the same time, WQ parameters (transparency, turbidity, total suspended solids, and particulate phosphorus) were measured from grab samples. Evaluation of the results showed that the common human perception was in accordance with the measured parameters that influence visible characteristics of water.

Another older experiment was carried out for the rapid quality assessment of several samples of wastewater by seven laboratory technicians and field scientists as observers [5]. They were asked to estimate of the amount of total suspended solids, chemical oxygen demand (COD), and biological or biochemical oxygen demand (BOD) visually and the results show that field scientists gave twice as many good answers (with an error of 10% max) than the laboratory technicians. Even if the number of observers was small, this experiment shows that experimented people seem to be better observers.

Nowadays, people can be more easily involved through social networks and smartphone applications such as Hydrocolor or Eyeonwater (EoW). This application allows anybody to take a picture of the surface of a water body and upload it on their website "eyeonwater.org." The color is codified by virtue of a visual comparison with the Forel-Ule (FU) hue scale when the picture is uploaded by the observer (see an example in Fig. 1.2). A recent work comparing the two applications [6] concluded that there is a degree of confidence for the FU scale within the EoW App, which is appropriate and provides a fairly accurate estimation of WQ. However, the EoW App with the use of FU scale should not be considered as a surrogate for other WQ variables (parameters).

IV. CONCLUSION

In order to eliminate problems associated with manual water quality monitoring, Central Pollution Control Board (CPCB) has planned to go for hi-tech solution. CPCB is planning to install 'Real Time Water Quality Monitoring Network' across Ganga Basin for testing ten parameters. The Ganga is the largest and the most important river of India, with its watershed covering 10 Indian states, namely Uttaranchal, Uttar Pradesh, Bihar, Jharkhand, West Bengal, Himachal Pradesh, Rajasthan, Haryana, Madhya Pradesh and Delhi. Discharge of untreated sewage from urban centres is a major cause of water quality degradation in the river. The total wastewater generation from 222 towns in Ganga basin is reportedly 8250 MLD, out of which 2538 MLD is directly discharged into the River, 4491 MLD is disposed into its tributaries and 1220 MLD is disposed on land or low lying areas. "River Yamuna is one of the most grossly polluted rivers in the country. There are number of inter-state issues and events of episodal pollution. In case of Ganga, we have to address large number of petitions, RTIs, VIP references etc and the NGRBA is constituted for large scale investment towards STPs etc", says Dr R M Bhardwaj, Senior Scientist, Central Pollution Control Board

The parameters that CPCB plans to monitor online are pH, turbidity, conductivity, temperature, Dissolved Oxygen, Dissolved Ammonia, Bio-chemical Oxygen Demand, Chemical Oxygen Demand, nitrates and chlorides. All the stations will be operational in real time mode and central station will be able to access data from any of these stations. The stations will also be tolerant to extreme environmental conditions in India such as high or low temperature, high humidity coastal conditions and high temperature desert conditions. Moreover, the stations will be such that it won't require manual intervention for at-least 5 years, except for routine calibration and battery replacement.

All the water quality monitoring stations will be fitted with GSM, GPRS for communication with the central receiving station. The central receiving station will have software for data acquistion, data analysis, data display and report generation. Zonal offices of CPCB and State Pollution Control Boards will have direct access to the data from central receiving station. "This is a pilot study. There are success stories in the western world. Technology is available and being used overseas. There are success stories with Continuous Air Quality Monitoring and we hope to achieve success in real time water quality monitoring also. There is major shift in the communication system for transmission of data and the same will be utilised for remote vigilance in the case of water quality also" says Dr Bhardwaj.

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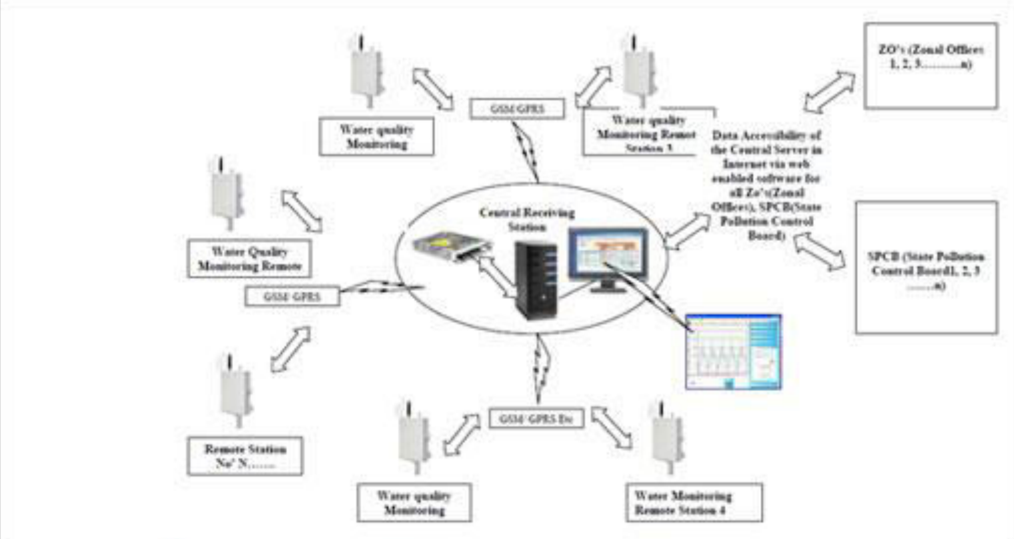
Figure 1: How system works?



Source: Central Pollution Control Board

"Earlier, with manual sampling we used to get analysis report of one sample in a month. But with real time monitoring, we will get at least 50 and a maximum of 95 data every day. Regular and large number of data will enable us to take decision which can be implemented on time and is effective", adds Dr Bhardwaj.

Cost the limiting factor

Despite, good features and reliability cost of instruments for testing water quality may become a hindrance for Boards. Costs of instruments are dependent on parameters to be measured. In case, one needs instruments to monitor all the ten parameters, then the instrument will cost Rs 35-40 lakhs and operation and maintenance will be carried out by the supplier. Since, the data quality and data availability is an issue; there will always be a temptation to upscale the project to more monitoring stations. This has a huge financial implication. Nevertheless, it is not a bad choice considering poor quality data available for policy-makers. "Funding is always an issue even for manual monitoring. Need based automation is the requirement and possibility will be explored to gather funds for specific areas/rivers" concludes Dr Bhardwaj. [24]

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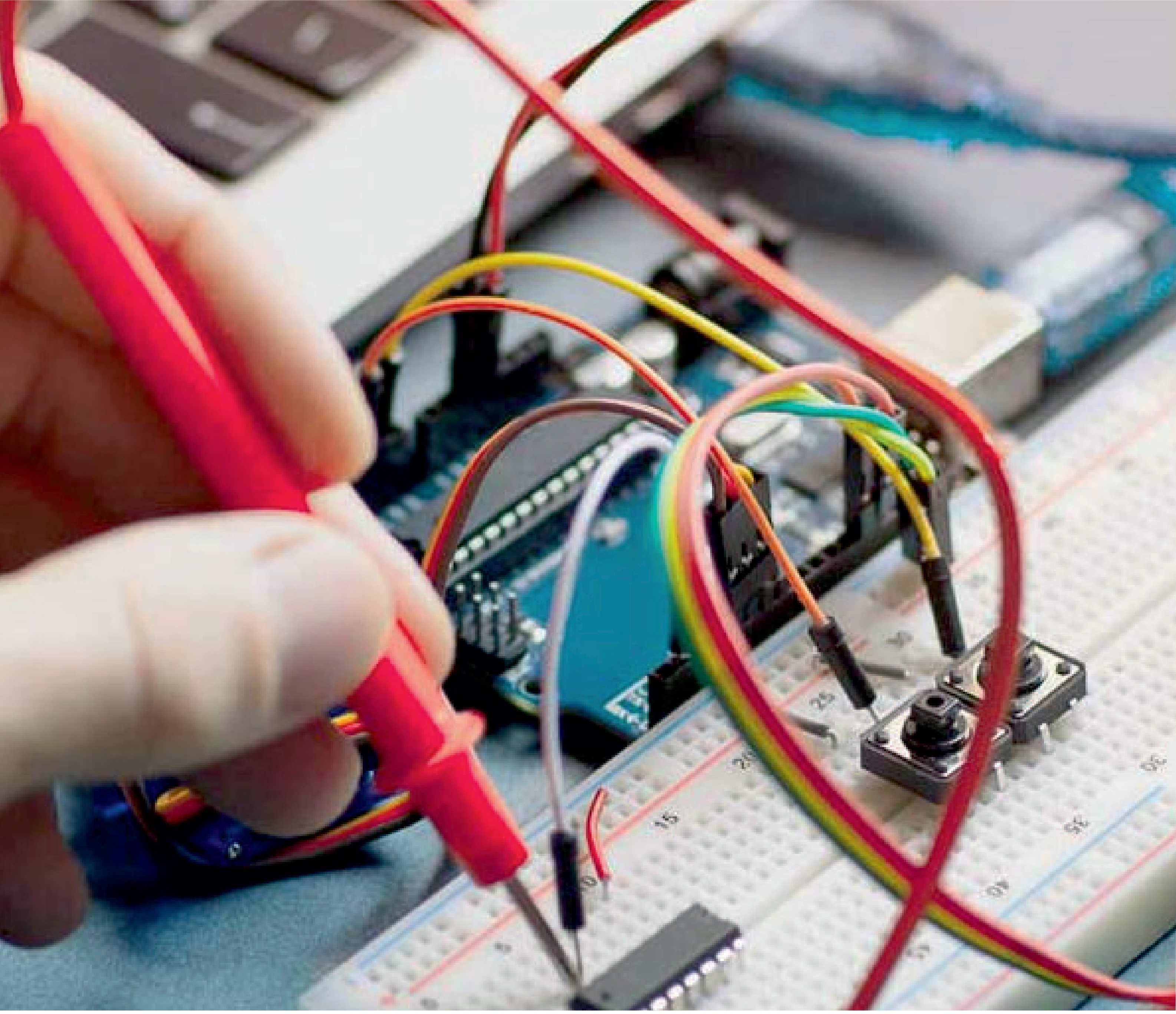

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