HydroSignal: Open-Source Internet of Things Information Communication Platform for Hydrological Education and Outreach

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Abstract

This study introduces HydroSignal, a low-cost, open-source platform designed to democratize hydrological monitoring by leveraging the power of Internet of Things (IoT) technology. With its web-based interface, HydroSignal aims to make vital hydrological data easily accessible to a wide range of users, including professionals, educators, and students, thereby promoting improved environmental awareness. Through the integration of IoT devices and user-friendly visualization elements, HydroSignal facilitates the real-time acquisition and presentation of various hydrological parameters. The platform's versatility is demonstrated through the four distinct use cases including, but not limited to, flood level and turbidity monitoring, rainfall data visualization, and simultaneous monitoring of soil moisture and temperature. These applications highlight HydroSignal's capability to support professionals, educators, and students, promoting an in-depth understanding of hydrological processes and environmental management. Demonstrating its versatility with applications ranging from monitoring water quality to providing flood level, HydroSignal improves our understanding and management of water resources. HydroSignal offers a promising solution pioneering for hydrological and environmental monitoring, improving the accessibility, communication, and visualization of data, and facilitating an interactive learning experience in hydroscience education and community engagement.

Keywords: Hydrological Monitoring, Internet of Things, Environmental Data, Real-Time Monitoring, STEM Education, Data Visualization.

Software Repository: https://github.com/uihilab/HydroSignal

1. Introduction

Hydrological monitoring, the science of observing and analyzing the distribution, movement, and quality of water in natural and built environments, is essential for informed decision-making in water resource management (Sermet and Demir, 2023). This scientific process involves collecting and analyzing data related to water flow, quality, and distribution, which are vital for effective water management, flood control, and environmental monitoring (Ramirez et al., 2024). Reliable and real-time monitoring of water resources is critical to minimize the loss of life and property from water-related hazards and the effective management of water resources (Guo, 2010; Alabbad and Demir, 2022). The high cost of deployment and maintenance of these monitoring systems (including electronics, sensors, hardware, software) causes challenges for data coverage, which is crucial to tackle vital issues like natural disaster mitigation (Yildirim et al., 2022; Cikmaz et al., 2023), water resource management, and climate change (Khan et al. 2020).

Hydrological monitoring has traditionally been resource-intensive and complex, limiting access to data and understanding to a relatively small group of specialists (Herschy, 2009; Dadson et al., 2019; Demir and Szczepanek, 2017). However, the integration of IoT technology has begun to democratize access to hydrological data (Drost et al., 2022), making it possible for a wider audience (Ketchesonn et al., 2023) to engage with and understand these critical systems. IoT technologies have transformed traditional hydrological monitoring systems into dynamic, interconnected networks that deliver precise and timely data, essential for addressing complex environmental challenges (Ahmet et al., 2020; Xiaocong et al., 2015).

The advent of IoT-based technologies in hydrology has facilitated a significant enhancement in data collection methods, analysis, and accessibility (Geetha et al., 2016; Sit et al., 2021). These technologies enable the deployment of sensor networks across diverse and remote aquatic environments, capturing critical data on water quality, level, flow, and precipitation with unparalleled accuracy and frequency (Demir et al., 2009). Real-time data acquisition is pivotal for understanding hydrological processes (Li and Demir, 2022), forecasting water-related disasters (Sit et al., 2021; Krajewski et al., 2021), and managing water resources efficiently.

Researchers have been continuously working on the IoT based state-of-the-art hydrological monitoring technologies employing public networks (Ketchesonn et al., 2023; Abdelal et al., 2021), smart sensors (Zhang et al., 2019), cost-effective (Panjabi et al., 2018) and real time (Zhang et al., 2017) approaches. Although these technologies are mostly focused on water quality monitoring, other hydrological monitoring studies such as flood monitoring (Zakaria et al., 2023; Li et al., 2023), drainage monitoring (Omamageswari et al., 2021; Guidani et al., 2022), and water induced landslide monitoring (Oguz et al., 2022) have also been carried out more recently.

One potential application area for IoT based hydrological monitoring is in hydroscience education. There are many challenges to integrate any tools or platforms into hydrology related curriculum (Pursnani et al., 2023; Ewing et al., 2022). Generally, instructors have barriers to create or use successful educational applications due to resource or time limitations (Jackson, 2014; CrowdFlower, 2016; Anaconda, 2020). Most of the time, the instructor needs real-time monitoring of data in a short time, especially in the classroom example. Thus, this creates strong pressure for the instructor between teaching fundamental science and teaching the complex tool. This reality describes the challenge to teach contemporary hydroscience topics in a manner, which recognizes the state-of-the-science tools, without obscuring the subject fundamentals behind the technical or vocational knowledge of specific software or tool chains.

By integrating software, web and AI technologies, online platforms seek to provide tools that not only enhance the capabilities of professionals in analyzing and interpreting data but also engage and educate the public through outreach activities, such as interactive displays and gamified learning experiences (Demir et al., 2022). One example is HydroViz which is suitable for senior-level students and is aiming to improve undergraduate hydrology education (Habib et al., 2012). In another recent study, researchers created an educational, web-based platform, HydroLearn, for the instructors to collaboratively develop, share and adopt active-learning resources in hydrology and water resources engineering (Lane et al., 2021). In addition, the authors develop an open-source software, Sandtank-ML, which allows users to gain an understanding of basic machine learning (ML) concepts and address hydrological processes (Gallagher et al., 2021).

On the other hand, several open-source software solutions used novel web technologies to develop web applications for water resource management (Swain et al., 2015; Jadidoleslam et al., 2020). Among these, Python and Django based Tethys framework (Swain et al., 2016), R based SHARKS web application (Brendl et al., 2019) and JavaScript based HydroLang (Ramirez et al., 2022;) can be shown as examples that require advanced programming language knowledge and third-party dependencies. Major challenges with these open-source software platforms are that they are complex, comprehensive, and especially suitable for environmental scientists and graduate students (Erazo et al., 2023). In addition, they do not contain any hardware components that motivate students to develop hand-on skills and analytical thinking, and they are not simple enough to be suitable for both the non-expert users and the STEM students.

Many open-source software solutions developed for hydrology require a database system to handle the complex hydrological data (Shahid et al., 2023). However, the database requirement of these solutions poses a major obstacle for a user with limited database management expertise. The use of data services for sharing and accessing information has grown in popularity among providers of environmental data. An example of this is the HydroClient offered by the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI), which allows users to access data through an interactive web-based platform for a selected region. Similarly, the National Oceanic and Atmospheric Administration (NOAA) provides a web service that grants users access to a broad range of environmental observations. Recent enhancements in web technology have introduced new capabilities that support the creation of applications using native web programming languages, like JavaScript. This is further exemplified by the standardization of JavaScript in line with the modern ECMAScript standard (ECMA, 2021), which has greatly alleviated compatibility issues across various web browsers (Walker and Chapra, 2014).

The concept of HydroSignal draws inspiration from innovative projects like Google's Paper Signals (Paper Signals, 2017), which demonstrated the potential of combining IoT with user-friendly interfaces for interactive and real-time data communication. Google's Paper Signals project was an experiment in blending physical and digital worlds, allowing users to create simple paper devices that could track and display information from the internet, such as weather changes or rocket launches, in real-time. This project exemplified how complex data could be communicated in a simplified and engaging manner. Building on the idea of Paper Signals, HydroSignal aims to adapt this concept to hydrological monitoring. By integrating intelligent assistants and IoT technologies, HydroSignal envisions creating a system where hydrological data is not only collected and communicated in real-time but also presented in a manner that is engaging and accessible to professionals, educators, and the public alike.

The aim of this study is twofold. First, we seek to develop low-cost, open-source, and easy to use IoT based hydrological monitoring packages including electronics, software, and visualization elements. Second, we seek to empower professionals, educators, and students for hydroscience and environmental awareness. Toward these aims, we develop an IoT based and open-source application, HydroSignal, to access data related to the various hydrological parameters taken from real sensors in the field, and to control active visualization elements. Furthermore, we also present how to design an active visualization element without needing extra knowledge, and to implement it into HydroSignal without needing extra electronics and hardware.

One of the main motivations behind this study is to demonstrate low-cost, open-source platform, HydroSignal, that is accessible to a wide range of educational settings, from primary schools to universities. Recently, one of the major science community initiatives (the Consortium for Universities for the Advancement of Hydrologic Science, Inc, CUAHSI) have stressed reforming the future of hydrological education and recommended the developments of open source, web-based platform for educational purposes (CUAHSI, 2023). By providing educators with real-time data and interactive tools, HydroSignal can transform how students learn about hydrological monitoring, and environmental management.

The educational implications of this transformation are profound, offering new avenues for experiential learning and engagement with environmental science. The platform's focus on gamification and interactive learning activities addresses the growing need for engaging educational content that can compete with the distractions of the digital age. Furthermore, HydroSignal represents an opportunity to cultivate a generation of informed citizens who are not only knowledgeable about hydrological systems but also equipped to contribute to their sustainable management. By bridging the gap between scientific research and public understanding, HydroSignal plays a crucial role in fostering environmental awareness and advocacy.

The remainder of this paper is organized as follows: Section 2 describes the proposed methodology along with a comprehensive description of system architecture, system components including IoT device, web application, data formats, visual design element and how to implement. Section 3 presents how the HydroSignal works under the different use cases for hydrology and environmental science. Finally, Section 4 concludes the paper with a summary of contributions, and possible future directions to improve the HydroSignal tool and enable its use in different domains.

2. Methodology

This section outlines a detailed methodology for the HydroSignal platform with an overview of the system architecture, hardware components, web application layer, process of data flow and methodologies for retrieving information from remote sources, visual design template, covering its data format, type, structure taxonomy, and how servo motors' movements are synchronized with the visual design.

2.2. Architecture and Components

Figure 1 illustrates the architecture of the HydroSignal platform, showing the components and their interactions. The HydroSignal platform is designed as an IoT-based platform for hydrological monitoring, integrating a sophisticated combination of an IoT device, a web application, and remote data sources. This integration is guided by a user-centric design philosophy, aiming to empower users with the ability to seamlessly connect HydroSignal devices to remote data services for continuous hydrological change monitoring. Embedded with a specific visualization design, the HydroSignal devices offer users the flexibility to dynamically combine different data sources and devices, creating a personalized monitoring experience. This setup encourages a fluid exchange of hydrological data between remote sources and the HydroSignal application, enhancing the system's adaptability and efficiency.

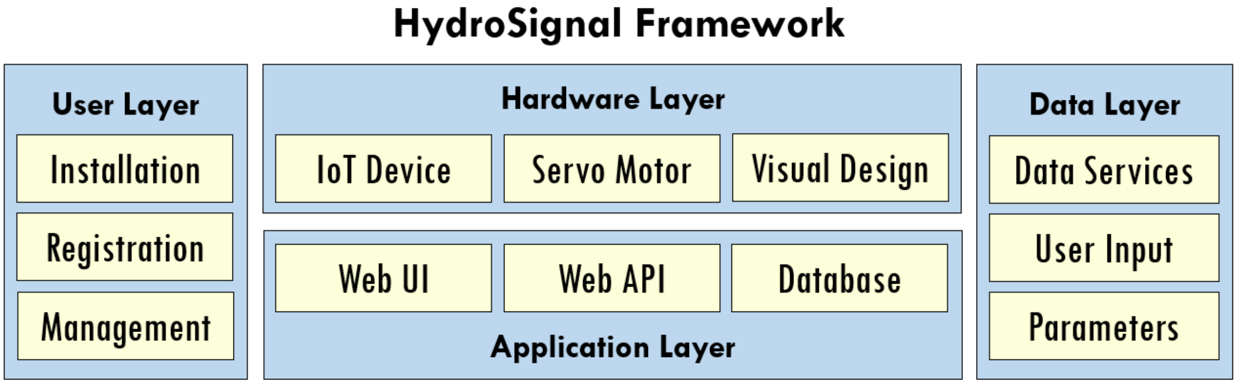


Figure 1. The framework and components for the HydroSignal-IoT based hydrological monitoring system.

The system's hardware component is user-installed, tailored to the specific design of development HydroSignal. This hardware includes an IoT device, a servo motor, and a visualization design. The IoT device is the main component of the HydroSignal platform, serving as the primary conduit for data communication and the control center for the servo motor. The inclusion of a servo motor enables visual design to perform precise movements, which are essential for the operation. Users can remotely customize the settings of the IoT device via the web application, which communicates with the Web API to fetch necessary data. This feature ensures that users are not required to make manual adjustments to the device after its initial setup.

The Web User Interface (UI), developed using ReactJS, is designed to facilitate seamless online configuration of data flow for IoT devices. It offers a user-friendly and adaptable interface for device registration and configuration, allowing users to monitor data from any JSON-compatible web service address. The Web UI system architecture encompasses both a frontend and a backend. The frontend offers easy device configuration through the web interface, while the backend, developed in Node.js, handles configuration changes initiated by users, data retrieval from remote web services, and processing device requests. The Web API acts as the foundational element for backend operations, serving both the user interface and device functionality. This demonstrates the versatility and effectiveness of Node.js in the system's development.

It is important to recognize the role of remote data services in the HydroSignal platform. Users select these services based on their JSON compatibility, which is crucial for translating the data into angular movements performed by the IoT devices. The system requires that data from these sources can be converted into an angular value, as direct modification of the data from remote sources is not supported. Therefore, details such as the service address, the complete data path, and the value range of the filtered data are critical for the system to perform effective monitoring.

2.3. Hardware Design

The HydroSignal platform is designed with a solid hardware foundation consisting of an IoT device paired with a servo motor (shown in Figure 2), a configuration designed to leverage the full potential of modern hydrological monitoring technologies. This section details the features, integrations, and operational dynamics of each component that supports the functionality of the platform.

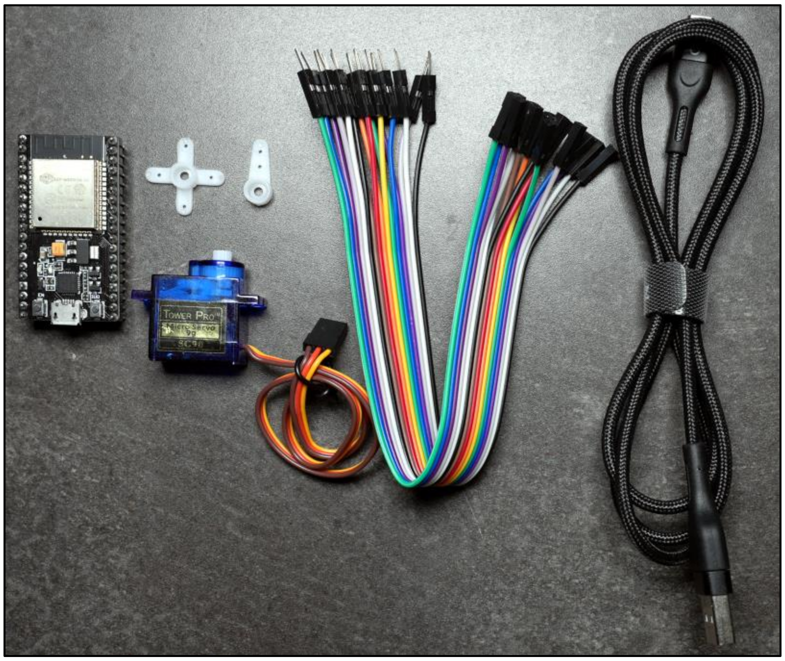


Figure 2. The Hardware components of HydroSignal platform include NodeMCU with ESP32 Wi-Fi chip, servo motor, male/female extension cables and USB cable.

2.3.1. Hardware Components

The main component of the HydroSignal hardware architecture is an IoT device, a Wi-Fi-enabled development board embedded with a microcontroller unit (MCU). This board stands out for its programmability, offering users the flexibility to adapt its operation with simple coding applications. It dynamically controls a servo motor via PWM (Pulse Width Modulation) outputs, a process that is calibrated based on angular data from the HydroSignal Web API. The importance of IoT devices, especially those using Espressif's Encapsulated Security Payload (ESP)-based protocol, cannot be overstated. Adoption of the protocol is trending upward, as evidenced by the widespread use of NodeMCU development boards.

These boards, incorporating the advanced ESP 32-based MCU alongside a dedicated power unit, have found extensive applications across various IoT domains, such as hydrological monitoring (Abdelal et al., 2021; Marino et al., 2023), water quality monitoring (Durga et al., 2022), flood warning systems (Mamat et al., 2021), and water level monitoring (Krishnaveni et al., 2020; Mamat et al., 2022). In particular, their design emphasizes user-friendliness, extensibility, and modularity, which are the most important features for widespread adoption of the HydroSignal platform among various user groups, including STEM students, undergraduate students, and the public. Delving deeper, NodeMCU emerges as a very important element within this ecosystem. It stands out with open-source LUA-based firmware designed specifically for Espressif's ESP32 Wi-Fi chip, marking a milestone in IoT device programmability.

The availability of NodeMCU firmware simplifies the programming process through compatibility with the Arduino Integrated Development Environment (IDE) via a USB connection when paired with an ESP32 Development board and requires the installation of an ESP32 library. This aspect is crucial to fostering a supportive community ecosystem where users can easily access a wealth of library support, increasing the usability and adaptability of the HydroSignal platform. By incorporating the CH340 or CP2102 USB-to-serial programming chips into the NodeMCU development board, programming the device is simplified and the need for auxiliary hardware is eliminated.

The firmware of the IoT device developed for the HydroSignal platform is shared as open source on GitHub. This approach allows users to load the provided code directly onto NodeMCU development boards using the Arduino IDE. The operational logic of this firmware includes periodic communication with the HydroSignal Web API to retrieve and update the angle settings of the servo motor; this flow is shown in Figure 4. The initial setup function, performed once when the device is started, and the subsequent loop function, which runs indefinitely, are critical for configuring library settings (including Wi-Fi and servo motor pins) and maintaining continuous angle settings, respectively.

The integration of the SG90 model servo motor with the IoT device forms the mechanical action arm of the HydroSignal platform. This motor, chosen for its balance of torque (2.5 kg-cm) and speed (0.1 s/60°), facilitates precise angular adjustments crucial for the HydroSignal's operation. Its design enables rotation within a 0° to 180° range, adequately meeting the project's requirements without necessitating high torque levels, given the lightweight nature of the materials involved.

Finally, the practical assembly of the HydroSignal platform requires attention to the NodeMCU and servo motor connection, ensuring proper alignment and connectivity of relevant pins for operational efficiency. The NodeMCU's pin layout, illustrated in Figure 3, along with detailed instructions for connecting the servo motor, underscores the importance of accurate setup for seamless operation. This setup includes connections for power (VIN, 5V), ground (GND), and the PWM signal (GPIO12), facilitating the servo motor's controlled movements.

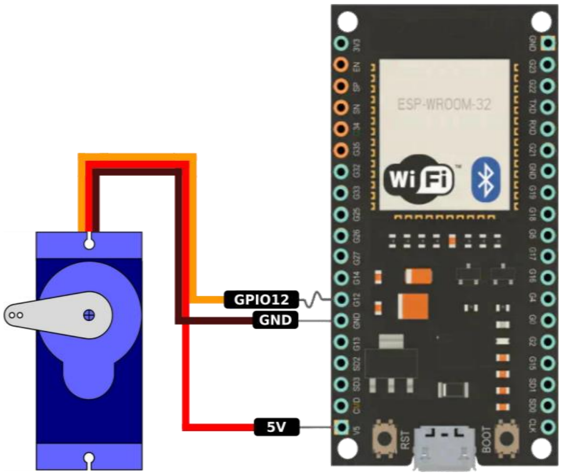


Figure 3. Pin definition of NodeMCU and connection diagram of NodeMCU and servo motor.

2.3.2. Device Connectivity

Upon the device's initiation, the Setup function is executed a single time to configure essential components for its operation. This initial configuration encompasses preparing the servo library and setting up the servo motor's parameters using the PWM output pin, a critical step for ensuring precise control over the motor's movements. Additionally, the ESP Wi-Fi MAC address is read to uniquely identify the device, a measure that aids in its secure and efficient integration into networked environments. Following this, the Wi-Fi Manager library is initialized, establishing a Wi-Fi connection that serves as the backbone for the device's communication capabilities. After the Setup phase, the device transitions into the Loop function, entering an infinite operational cycle that persists for as long as the device remains powered on.

The first step in this cycle is to secure a successful Wi-Fi connection, upon which an HTTPClient is initiated. This client plays a pivotal role in facilitating web requests, starting with establishing a connection to the HydroSignal API address using the http.begin(api_address) command. A subsequent http.get() request dispatches the HTTP query. In cases where the web API returns a 200 HTTP status code—a confirmation of no issues—the response's JSON data is parsed to extract the angle value. This crucial piece of information is then accurately written to the servo motor, adjusting its position as required by the application's current needs. This loop ensures the device remains responsive and up to date with the latest commands and settings from the

HydroSignal platform, highlighting the seamless integration of hardware and software in achieving sophisticated control and monitoring capabilities.

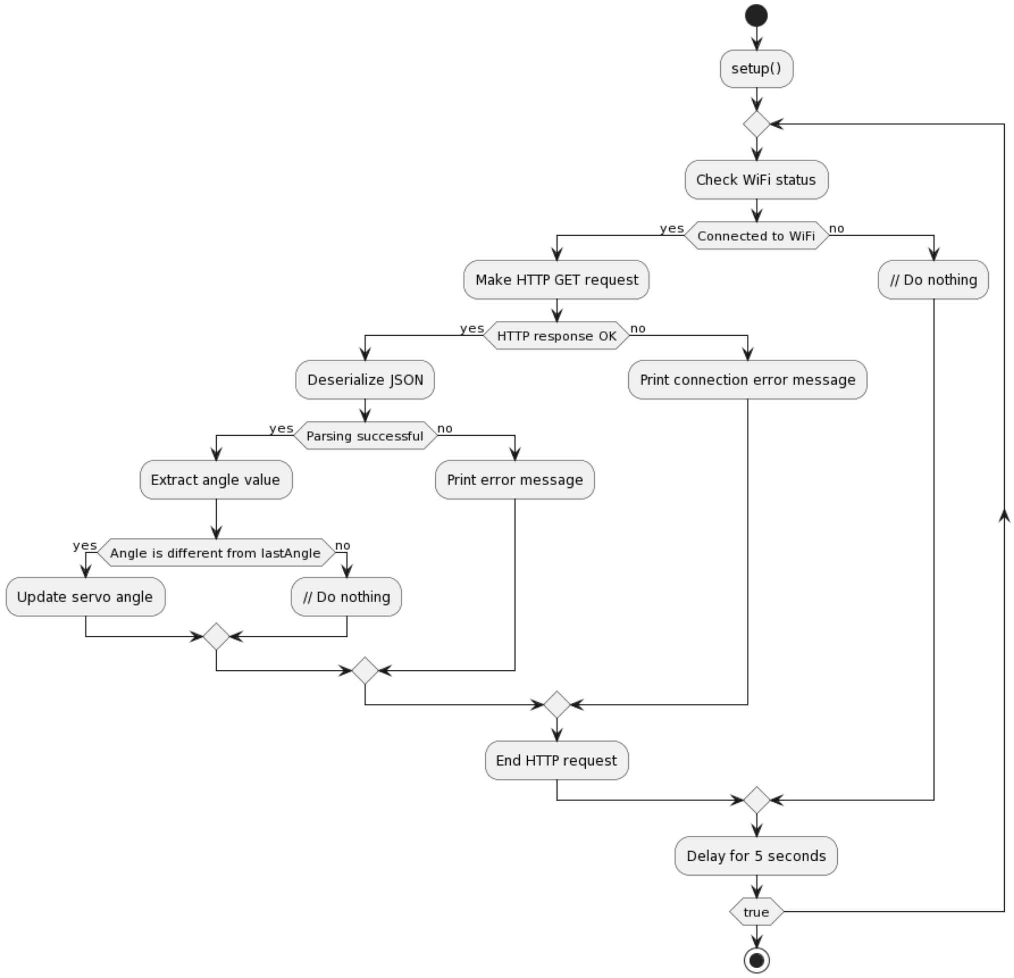
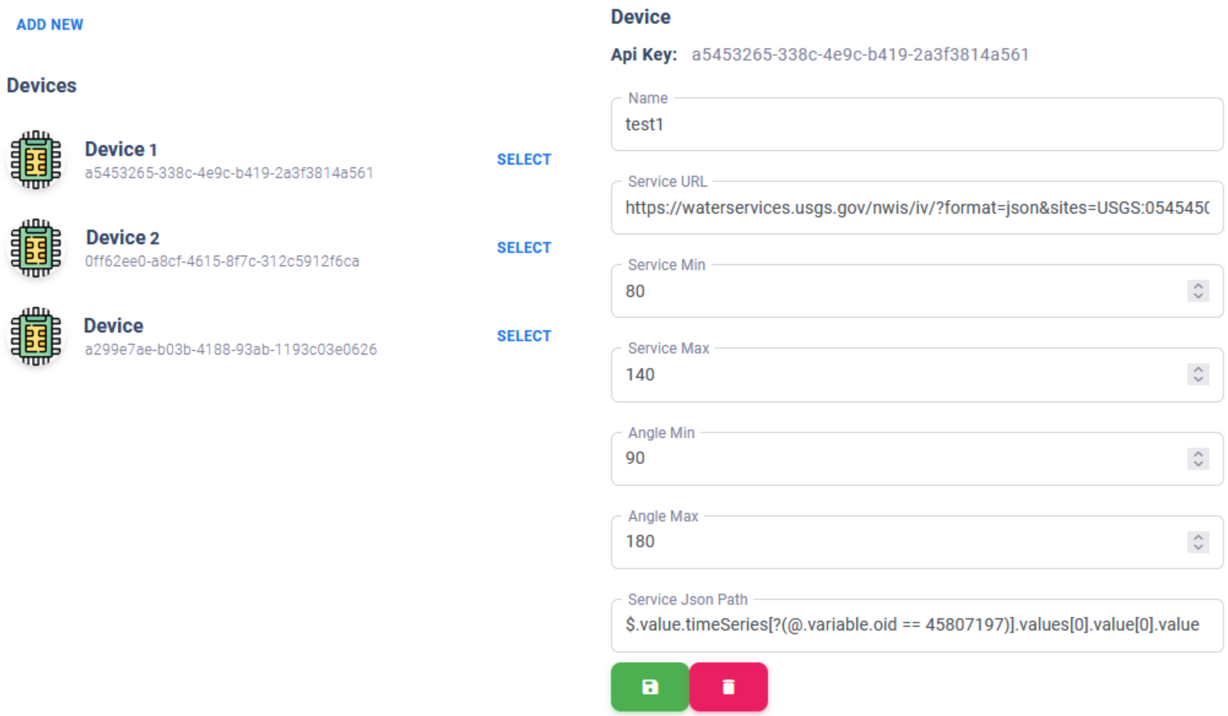


Figure 4. Firmware logic flow diagram of HydroSignal platform through Web API.

2.3.3. Device Registration

It is important for users to include their unique API keys in the IoT firmware code before the firmware is loaded onto the IoT device. This API key serves as a crucial component for authentication during the device's communication with the HydroSignal Web API. This is a unique identifier that users must obtain through the HydroSignal Web User Interface (UI) as part of the device registration process (shown in Figure 5). A special parameter is assigned in the firmware's code for the API key, which requires users to enter their distinctive ID, which they receive from the HydroSignal Web UI. The process of registering the device in the HydroSignal Web UI serves a dual purpose. It does not only facilitates obtaining the API key, but also allows users to customize parameters for the data tracked by the device.



Devices

Device 1 a5453265-338c-4e9c-b419-2a3f3814a561

Device 2 0ff62ee0-a8cf-4615-8f7c-312c5912f6ca

Device a299e7ae-b03b-4188-93ab-1193c03e0626

Device

Api Key: a5453265-338c-4e9c-b419-2a3f3814a561

Name: test1

Service URL: https://waterservices.usgs.gov/nwis/iv/?format=json&sites=USGS:054545

Service Min: 80

Service Max: 140

Angle Min: 90

Angle Max: 180

Service Json Path: `$.value.timeSeries[?(@.variable.oid == 45807197)].values[0].value[0].value`

Figure 5. Web User Interface (UI) for HydroSignal IoT device registration.

2.4. Web Application

The Web Application block of the HydroSignal platform combines front-end and back-end units to create a seamless user experience for managing hydrological monitoring devices. This separation is important for understanding how the platform works. Developed with ReactJS, the front-end offers a user-friendly interface for device management, including adding, modifying and deleting devices. This part of the application meets users' needs and allows them to interact with the system through forms and controls designed for intuitive navigation and configuration of device settings. Complementing the front-end, the backend powered by NodeJS supports the functionality of the platform by processing API requests initiated by user actions on the frontend. Integrating the PostgreSQL database and remote data source connections, this backend architecture manages business logic and data management, providing a responsive and efficient service.

The underlying goal of the HydroSignal Web User Interface (Web UI) is to enable users to manage their IoT devices efficiently. Through this interface, users can register devices, specify data sources, and set angular transformation parameters. The design of the UI focuses on ease of use, allowing editing of device configurations and data sources directly online. Leveraging ReactJS, Web UI ensures that all operations, from device registration to configuration updates, run smoothly, fostering an environment where users can control their devices with minimal effort. The device management interface shown in Figure 3 provides an open and accessible platform for users to add, list, edit and delete devices, providing a comprehensive tool for device surveillance within the HydroSignal platform.

When adding a new device, the application asks the user for basic information such as the name of the device, the service URL, and the minimum and maximum values for both the service and the angular movement of the servo motor. Following this, a unique ID is created for the device and stored in the database, linking it to the user's account. This process also includes storing an API key for each device; This is a crucial step to integrate the device with the wider functionality of the HydroSignal platform.

The role of the backend extends beyond just data management; It is the key element that connects IoT devices to the user interface, facilitating device configuration and data analysis for hydrological monitoring. This connection is achieved through the HydroSignal Web API, which provides a set of functions required for both device management and data processing. These include CRUD (Create Read Update Delete) operations for device configuration and a custom route for retrieving and processing hydrological data from remote sources. The angle data provisioning function is particularly critical as it transforms raw data into actionable insights and delivers the required angle values directly to IoT devices.

Device management in the Web UI is supported by these Web API functions, allowing users to perform various actions such as submitting new device data, saving configurations, and updating device details. The PostgreSQL database plays a vital role in this architecture by securely storing device configurations and ensuring that the HydroSignal platform remains reliable and compliant with open-source principles. Figure 6 outlines the device registration process, highlighting the streamlined integration of the HydroSignal Web User Interface with the backend infrastructure, showing the steps for device registration, API key generation, and IoT device configuration for instant deployment within the HydroSignal framework.

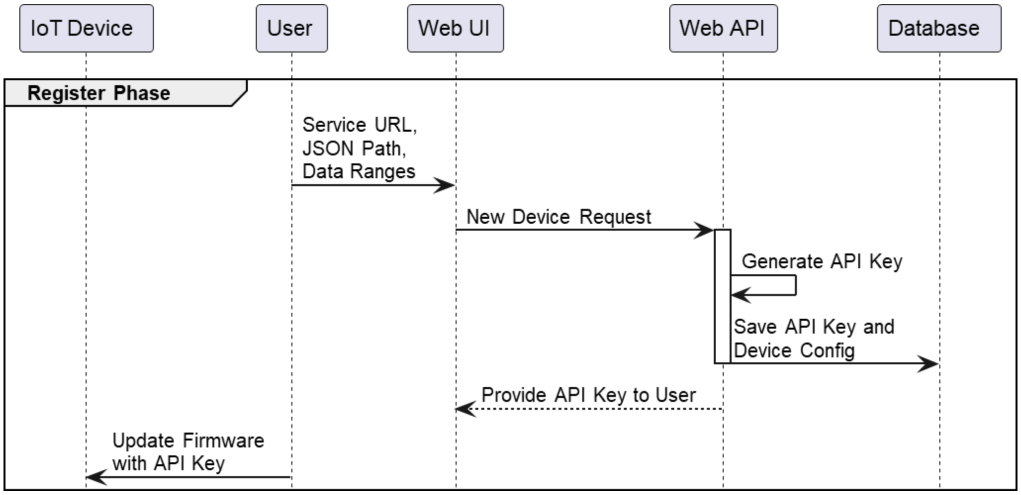


Figure 6. IoT device registration flow in the HydroSignal platform.

Furthermore, the Web API's interaction with remote data sources is a foundational aspect of the HydroSignal platform's functionality. It retrieves raw hydrological data from a variety of remote web services managed by national institutions like USGS (United State Geological Survey) and NOAA (National Oceanic and Atmospheric Administration), as well as public systems like

IFIS (Iowa Flood Information System). It also processes the data according to user-defined parameters and returns the necessary angle values for the operation of the IoT device and servo motor. This process involves advanced data filtering techniques and the application of specific formulas to convert raw data into the precise angle values for the IoT devices. The platform's reliance on JSONPath for data extraction and its formula for angle conversion exemplify the technical sophistication that underpins the HydroSignal platform, ensuring that IoT devices can perform monitoring tasks with accuracy and efficiency.

The initial step in processing the data involves sifting through the JSON data obtained from these services to extract only the pertinent information. This requires pinpointing the exact path within the JSON structure to the required data, a task accomplished using the JSONPath standard. JSONPath operates in a manner akin to XPath, which is utilized for pulling specific data out of XML documents, providing a powerful tool for navigating through JSON documents to extract the needed data. Users can specify the JSONPath, thereby enabling the retrieval of specific values from any JSON-producing web service with remarkable flexibility (Friesen, 2019).

Following the data extraction, the next critical phase is converting the filtered JSON data into an angle value, which is integral for device operation. This conversion process hinges on understanding the range of values obtained from the data service and the corresponding angle range within which the servo motor will operate. Achieving a proportional conversion from the raw data value to an angle necessitates the application of the following formula (Eq. 1). This formula represents a linear transformation used to map values from an input range to a specified output range. 'rawValue' represents the value coming from the service. 'inputMin' and 'inputMax' denote the minimum and maximum values of the input range, respectively. 'angleMin' and 'angleMax' represent the minimum and maximum values of the output range. The formula first normalizes the input value and then expands this normalized value to fit the output range. This is typically used to scale and transform input values to obtain desired output within a certain range.

$$Angle = \frac{rawValue - inputMin}{inputMax - inputMin} * (angleMax - angleMin) + angleMin \qquad \text{Eq. 1}$$

As a result, the Web Application of the HydroSignal platform is a holistic integration of front-end and back-end technologies that provides a robust and user-friendly system for hydrological IoT device management. This system not only simplifies device configuration and data analysis for users, but also reflects the HydroSignal platform's operation to innovation and user empowerment in the field of hydrological research by creating a reliable and effective framework for hydrological monitoring.

2.5. Data Workflow

This section defines the sequence in which data circulates within the HydroSignal platform, which includes the IoT device, servo motor, web API, and remote data sources. This flow is crucial to understanding how the system works, from the moment the IoT device initiates a request to the processing of that request by the web API and the final action taken by the servo motor in response.

Schematic overview of data flow in HydroSignal is shown in Figure 7, illustrating the three distinct phases: configuration, data, and action. This diagram depicts the sequential interaction among the IoT device, servo motor, Web API, and remote data sources, highlighting the HydroSignal's operational framework.

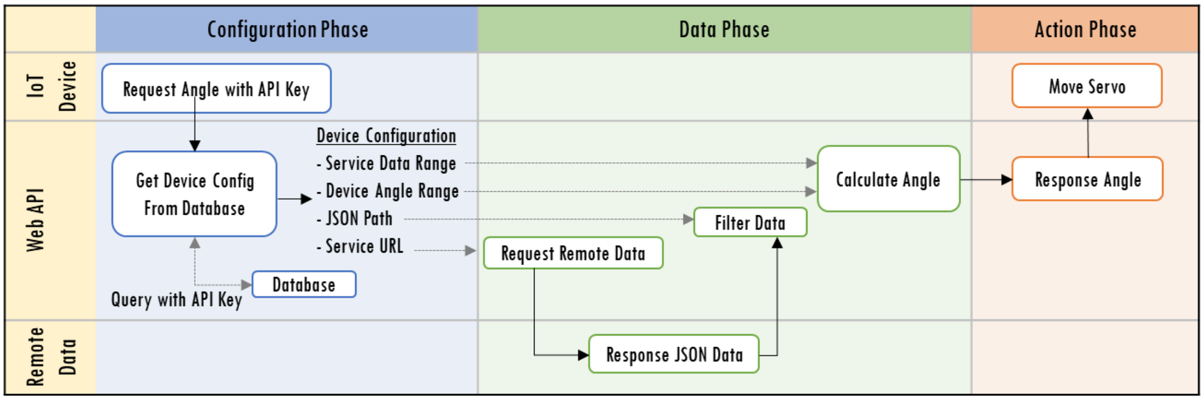


Figure 7. Schematic overview of data flow in the HydroSignal platform, illustrating the three key phases: configuration, data, and action.

Initially, the configuration phase sets the groundwork by establishing the parameters within which the IoT device operates. This is initiated when the device communicates with the Web API, leveraging its unique API key to retrieve its configuration stored in the system's database. The configuration fetched encompasses critical parameters such as the service data range, the device angle range, the JSON path, and the service URL. These parameters are indispensable for the subsequent data phase, providing the necessary details for data retrieval and processing. Following the configuration setup, the data phase commences with the Web API reaching out to the specified service URL to fetch the required data. The acquired data, typically in JSON format from remote data services, is then filtered to extract the precise angular value needed. This extraction utilizes the JSON path specified in the device's configuration, ensuring that the exact data point intended for monitoring is isolated from the broader dataset.

Upon isolating the desired data point, it must be transformed into an angular representation, a task managed by the Web API through a mathematical formula. This formula converts the raw data value into an angle by incorporating the service data range and device angle range specified by the user through the Web UI. These ranges define the data's minimum and maximum values and the corresponding angles at which the servo motor should position itself, facilitating an accurate physical representation of the monitored value. Once the data-to-angle conversion is completed, the IoT device transmits this angle to the servo motor using PWM signals. The motor then rotates to the specified angle to visually represent the monitored value. This marks the cycle that begins with the initiation of a request for data by the IoT device and concludes in the physical representation of this data by the servo motor.

Moreover, the process is constantly refreshed in the data update phase as shown in Figure 8. This phase illustrates the cyclical process where the IoT device periodically re-establishes communication with the Web API, prompting a re-evaluation of its settings based on the most current data. It details the steps of data retrieval, filtration, and conversion into servo motor angles, ensuring the system's data is consistently updated and accurately represents the latest remote service readings. This cycle highlights the platform's ability to integrate and dynamically respond within its monitoring framework.

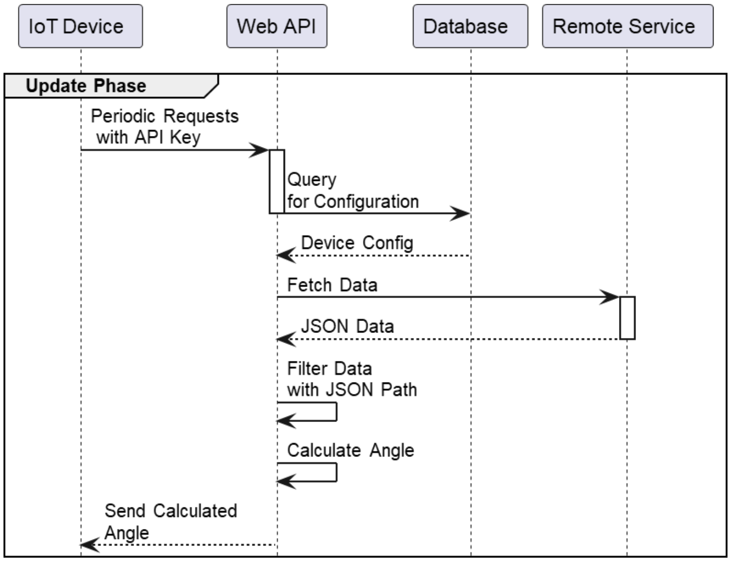


Figure 8. Data update workflow in HydroSignal platform.

2.6. Data Handling and Visual Design

This section introduces the data format, type and structures taxonomy as well as design of visualization template related to the data and motor movements according to design. Although the HydroSignal platform proposed in this study is designed specifically for visualizing data on hydrological parameters, it has the potential to be used for many different domains and sectors such as energy, transportation, geoscience, etc.

2.6.1. Data Handling

HydroSignal framework integrates data from a variety of remote service providers spanning national institutions and research-focused systems. Primary sources include physical sensor networks deployed onsite and predictive outputs from complex mathematical models. Additionally, the dataset includes alerts generated by comparing sensor readings to predetermined thresholds (i.e., flood alerts, warnings). These sources contribute data in multiple formats with numerical notation being the most common format. For example, data from sensors, measuring parameters such as soil moisture, air temperature, and wind speed, are typically presented in numerical terms, albeit in different resolutions, and units (e.g., 35% humidity, 20°C for temperature, 7 mph for wind speed).

Additionally, certain types of data are better suited to categorical labeling. For example, flood level severity can be categorized into clear and understandable labels like no flood, minor, moderate, major. These labels can provide clearer guidance for actionable answers than raw numerical data, especially for non-expert people. Text formatting is used for data where qualitative descriptions are more effective. For example, precise measurement of precipitation is less communicative to the public compared to simple descriptive terms (e.g., no rain, drizzle, heavy rain) that more effectively guide individual actions. Let's assume the amount of precipitation is 0.02 inches/hour, but it has no meaning for the public. Instead, the expression 'drizzle' is more meaningful to people at the point of acting (light rain and no need for an umbrella).

The HydroSignal platform centralizes and transforms this heterogeneous data into a unified numerical indicator, representing the latest aggregated state. This combination aims to simplify user interaction, focusing attention on the singular, ultimate value displayed through a visual format. The visualization is designed to not only present the current figure but also increase user understanding and engagement by showing the nature and origin of the data.

2.6.2. Visual Design and Capabilities

One of the core hardware elements of the HydroSignal platform is the paper or cardboard based visual design element where the user can simply visualize the hydrological parameter any way they want to present. These visual designs include completely new representations created and integrated into HydroSignal platform in order to communicate various hydrological parameters. Our goals with this design process are to (1) allow users to monitor hydrological parameters in a simple and easy way, (2) provide users to create and to use their own designs, (3) allow users to design visualization elements without high level design knowledge, and (4) enable different users (from K12 to professional- people having different educational background) to easily access and use it.

There are several parameters to affect visual designs such as data type and format, remote service, and servo motor movement. Among these, servo motor movement is the most critical component to create the most appropriate visual design according to the hydrological parameter to be monitored. Servo motors are designed for precise control but are inherently limited to an angular range of motion of up to 180 degrees. This constraint suits applications requiring angular motion, allowing visual design elements to be attached directly to the motor shaft and eliminating the need for further modifications (shown in Figure 9a). However, some design applications require linear motion, which poses a challenge due to the servo motor's rotation mechanism.

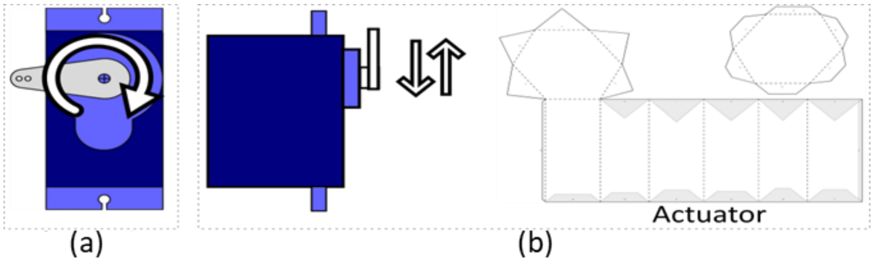


Figure 9. Illustration of servo motor equipped with a linear actuator, demonstrating the conversion of (a) angular and (b) linear motion.

The most common and effective solution to overcome this involves the implementation of a linear actuator. The first step involves orienting the servo motor in a horizontal position; but adding components for linear motion in this direction is not easy. At this point, the integration of a linear actuator is vital. Figure 9 shows the linear actuator component designed specifically for the project to facilitate the linear movements of the servo motor. This design includes a cylinder mounted at the base of the servo motor, which subtly converts rotational motion into linear motion along the side of the cylinder. This adaptation significantly increases the versatility of the servo motor, allowing it to be used in a wider range of visual design projects requiring precise linear motion.

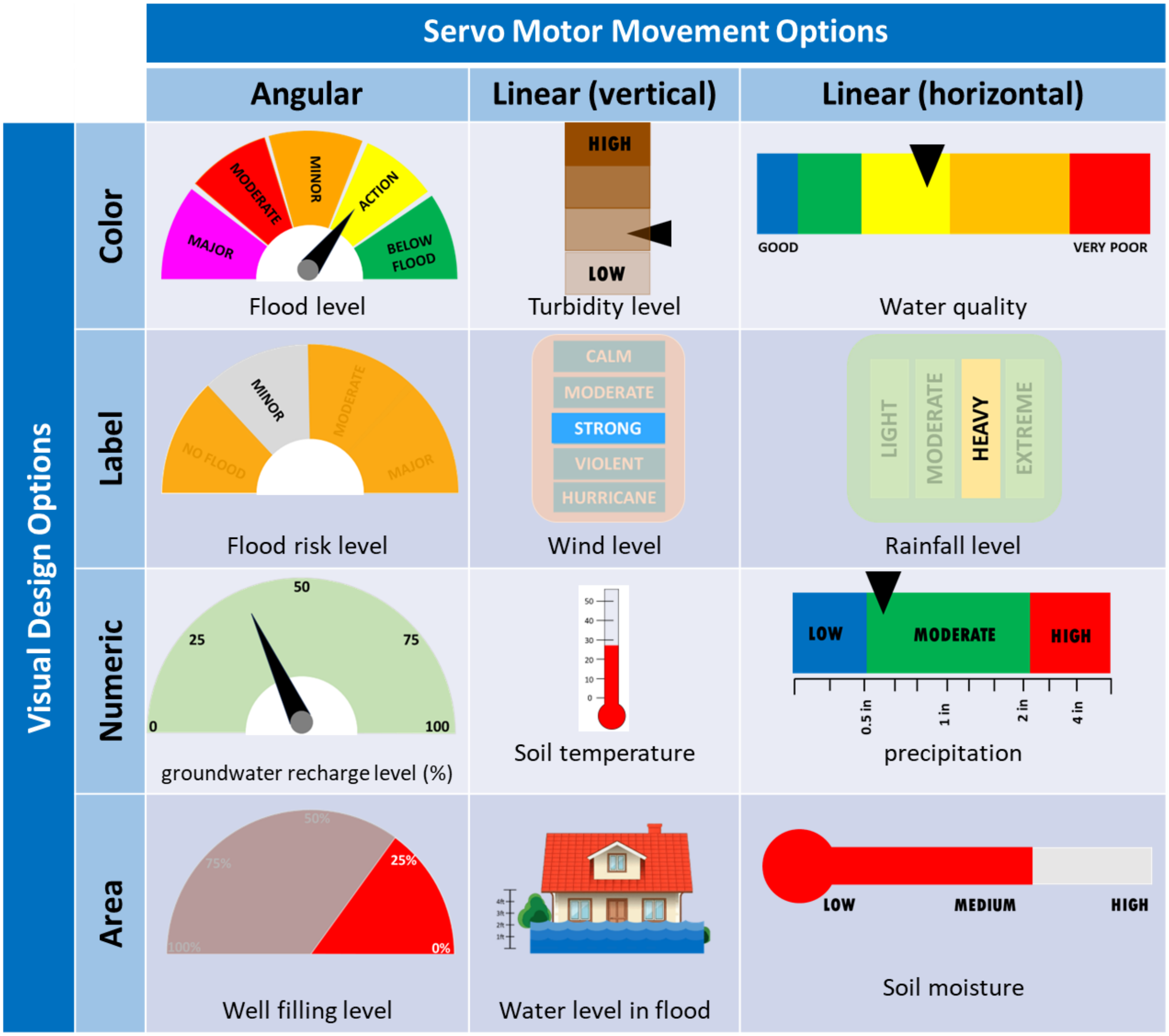


Figure 10. Visual design examples depend on servo motor movements and design options.

Since the focus of this study is the hydrology domain, various visual designs suitable for this are given in Figure 10, depending on the hydrological parameters and servo motor movement (angular or linear). The figure presents a structured overview of various visual design options for representing data through servo motor movements in three distinct categories: Angular, Linear (vertical), and Linear (horizontal). For each type of movement, we can suggest different visual representations based on color, labels, numeric values, and area. This matrix effectively organizes the visualization methods by the type of servo motor movement and the visual design approach, providing clear guidance on how to display various environmental data points. While similar designs can be used for different use cases defined in various domains, the user can also create application-specific designs and easily integrate them into the HydroSignal platform.

3. Results and Discussion

In this section, we provide four different use cases of the HydroSignal platform implemented by using different data types, formats, different remote service providers and different visualization designs. Each use case illustrates the different capabilities of the HydroSignal platform. Based on the specific use cases and visual design requirements, users can effortlessly assemble the HydroSignal's hardware components. The configuration of these components (including the servo motor, NodeMCU, cable, and visual design) within a paper-based enclosure is demonstrated in Figure 11(a) and (b), illustrating for both angular and linear motions of servo motor, respectively. Contrary to Figure 11(a) and 11(b) shows the use of a paper-based linear actuator component designed to provide linear motion.

(a) (b)

Figure 11. Illustration of the HydroSignal's hardware components as a ready to use package, demonstrating the (a) angular and (b) linear motion of the servo motor.

3.1. Use Case 1: Flood Level Monitoring

This use case demonstrates the process of monitoring flood levels through time-series data. The data acquisition is enabled through the United States Geological Survey (USGS) and Iowa Flood Information System (IFIS). While the USGS provides gauge sensor data, IFIS provides flood level maps based on these levels. Together, these services enable the determination of flood levels at specific coordinates. For this study, the Cedar River area was chosen. Initially, gauge level data for the Cedar River was collected from the USGS web services. Then, the pre-calculated IFIS flood maps corresponding to various flood levels can be consulted to obtain flood level information for a particular location. Using the gauge data from USGS, the appropriate IFIS map for the current flood level is selected.

The IFIS service then calculates the flood level for the given coordinates using map ID parameters. In this case, the focus is on a location near the Cedar River. The HydroSignal platform requests data facilitated by a special function to visualize the flood level. This function retrieves the gauge level from USGS, selects the corresponding IFIS map based on this level, and invokes the IFIS method to calculate the flood level at specific coordinates. Users can access this functionality through a custom function URL, requiring only the coordinates of the monitored location. All necessary parameters, including the monitored value's range (Service Min: 0 ft to Service Max: 5 ft) and the servo motor's angle limits (Angle Min: 0° to Angle Max: 180°), can be set via the Web User Interface (UI) as detailed in the device registration section. This setup process is critical for ensuring that the data visualization accurately corresponds with the physical movement of the servo motor, which is a central aspect of the HydroSignal design philosophy.

Figure 12 shows an example illustration of real-time flood level data from the USGS for a specified region of interest (single family house near the Cedar River). The design template chosen for this use case features a model house alongside an indicator that represents flood level. The indicator operates by moving vertically, providing a clear and intuitive visualization of water level changes. These illustrations, Figure 11(a) and 11(b), highlight the variation in flood levels (measured in feet) at different times.

The HydroSignal platform has been created with flexibility, allowing it to work with various visual designs such as building, dam and car, well and towel depending on the different regions of interest where the water level will be monitored. This adaptability is achieved by easily adjusting the rotation angles of the servo motor to match the actual water level values to be monitored. Therefore, the chosen visual design ensures broad applicability of the HydroSignal platform for water level monitoring in different scenarios.

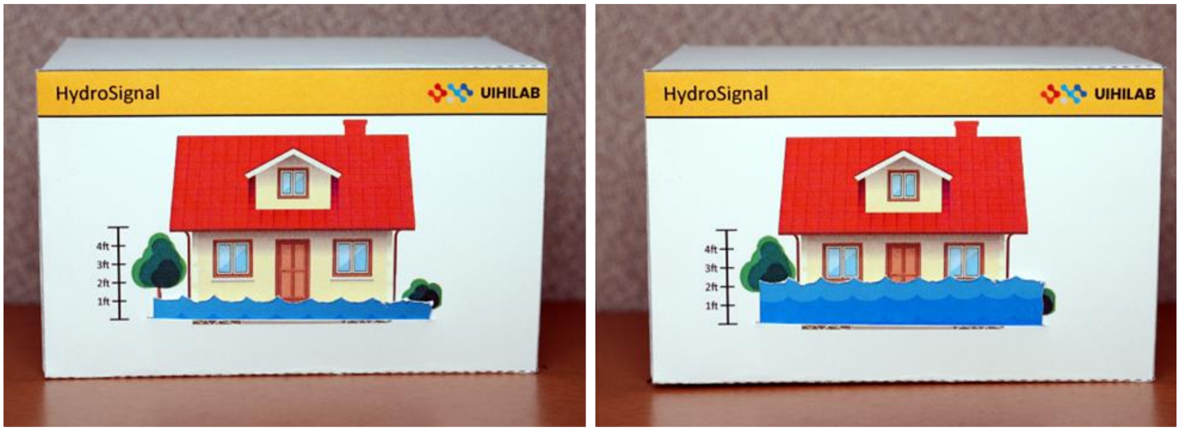


Figure 12. Example of real-time flood level monitoring (in feet) from USGS and IFIS for a single-family house near the Cedar River at Cedar Rapids, IA

3.2. Use Case 2: Turbidity Level Monitoring

This is an example HydroSignal use case for the monitoring and visualizing turbidity levels, a key indicator of water quality, through time-series data. The Iowa Water Quality Information System (IWQIS) web service was employed to gather turbidity data for Cedar River. After defining the monitoring device on the HydroSignal platform via the Web UI (device registration), the service's web address, JSON Path to filter turbidity data, the turbidity value's maximum and minimum levels (Service Min: 0 NTU and Service Max: 4000 NTU), and the servo motor's maximum and minimum rotation angles (Angle Min: 0° and Angle Max: 180°) can be entered through the Web UI. This preparation is very important to transfer the data from the IWQIS service to the visual design that aligns with the movement of the servo motor, allowing HydroSignal to monitor the data accurately and effectively.

Figure 13 presents visualization of turbidity data for Cedar River, employing a visual design activated by horizontal linear movement of servo motor. The HydroSignal platform is designed for versatility, supporting both the diverse visual designs outlined in Table 1 and user-customized visuals. Besides turbidity, the platform can monitor other vital water quality metrics such as nitrate, phosphate, temperature, pH, dissolved oxygen, and specific conductance. This is achieved using suitable visual designs through the IWQIS service, enabling comprehensive water quality assessment. Additionally, Figures 12(a) and 12(b) depict variations in turbidity levels (measured in NTU) over time for detailed insights.

HydroSignal's adaptability ensures the platform can accommodate various visual designs tailored to the specific water quality parameters being monitored. By adjusting the servo motor's rotation angles and designing appropriate linear actuators to align with the visual representation of the data, HydroSignal enables effective monitoring of water quality in different scenarios.

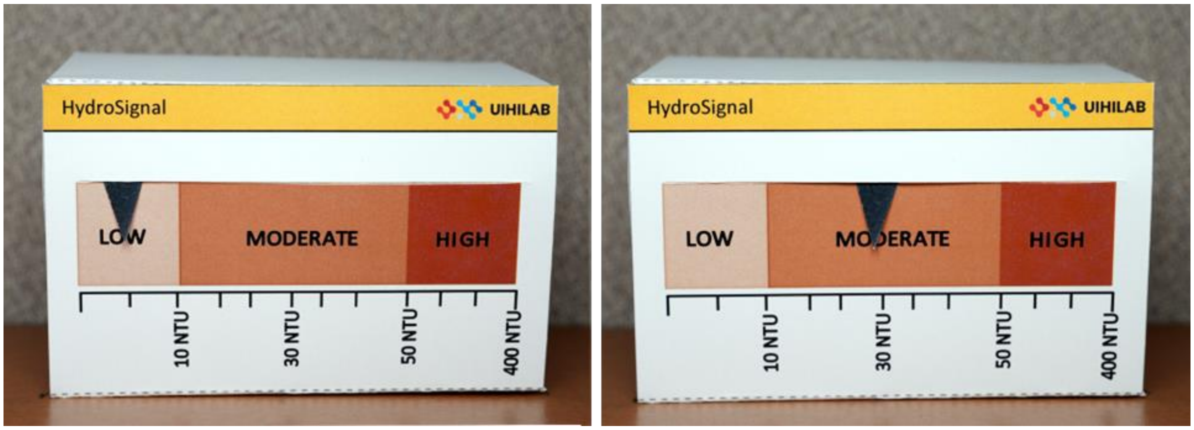


Figure 13. Real time visualization of turbidity level (in NTU) from IWQIS service for Cedar River at Cedar Rapids, IA.

3.3. Use Case 3: Rainfall Data Visualization

This use case illustrates the methodology for visualizing precipitation data categorized according to National Weather Service (NWS) standards using time series data. Data collection is supported by the National Weather Service as a remote service provider providing access to accurate precipitation data. Upon completion of device registration (mentioned in previous use cases), setup involves entering the service's web address, typing in servo motor's max/min angles and max/min levels of rainfall values. The servo motor's maximum and minimum angle settings are precisely calibrated within the Web UI to ensure that the representation of rainfall data corresponding to five levels matches the physical movement of an arrow attached to the servo motor. This setup ensures that the visualization accurately reflects categorically labeled rainfall data.

Figure 14 presents HydroSignal's output under two different rainfall scenarios, distinguishing and visually representing rainfall intensity changes for specific regions of interest. These scenarios are illustrated through a categorical visual design, where the rotation of the servo motor directs an arrow to the corresponding precipitation category label and color. The platform adapts to different visual designs (in this case, categorical labels for rainfall intensity) by simply adjusting the rotation angles of the servo motor. This flexibility ensures the broad applicability of the HydroSignal platform for visualizing precipitation data in various scenarios and improves the understanding and monitoring of weather patterns in various geographical locations.

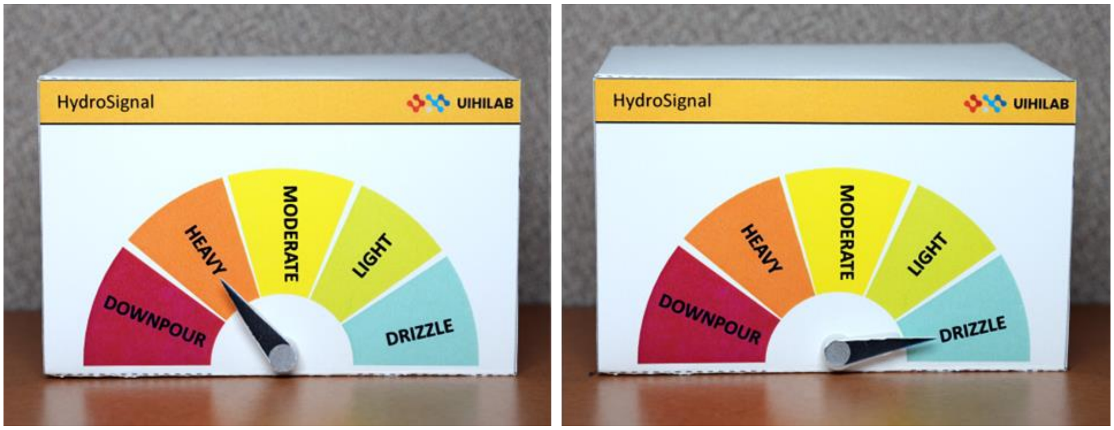


Figure 14. Example of rainfall intensity visualization from NWS under two different scenarios.

3.4. Use Case 4: Multi Variable Monitoring - Soil Moisture and Temperature

This use case demonstrates the simultaneous monitoring of two distinct time-series datasets: soil moisture and temperature, using a unified visual design. Data for this use case are sourced from the sensor named MROHYDRO001 located at Iowa City within the Iowa Flood Information System, reflecting HydroSignal's capability to integrate and visualize complex environmental data. Similar to the methodical categorization and combination approach outlined in the Use Case #1, this scenario utilizes a custom function that assigns indices to predetermined specific temperature (10-15°C, 15-20°C, and 20-25°C) and soil moisture (0-10%, 10-20%, and 20-30%) ranges. These indices are then combined using a following equation, creating singular value indicative of soil condition:

$$\text{combined\_value} = \text{temperature\_index} * 3 + \text{humidity\_index} \qquad \text{Eq. 2}$$

The HydroSignal platform leverages this value to visualize combined soil conditions visually through a servo motor's movement, converting the abstract data into a specific angle. The vertical visual design featuring a dual-window mask displays indicators, serving as the physical representation of this use case. This arrangement, with the indicators positioned in a semicircle behind the mask, allows for nine possible moisture and temperature combinations to be intuitively displayed, providing an accessible and simple interpretation of soil conditions. The monitoring process begins with configuring the device via the HydroSignal platform's Web UI, specifying the service web address as the custom function's address. This setup requires only the sensor ID and probe depth to extract values from IFIS. The servo motor's angle limits (Angle Min: 0° and Angle Max: 180°) and range for the indices (Service Min: 0 and Service Max: 8) are set to represent the nine combinations of moisture and temperature accurately.

Real-time visualization of soil moisture and temperature data is illustrated in Figure 15, with measurements depicting specific regions of interest over time. The visual design effectively segments data into three humidity ranges for each temperature category, offering nine distinct combinations of soil moisture and temperature for analysis. The design's adaptability allows for various grid configurations (e.g., 3x3, 3x4, or 4x4) to enhance monitoring resolution. Furthermore, the various visual designs outlined in Table 1 and user-customized designs can be used for this use case, demonstrating HydroSignal platform's capacity to support diverse visual designs. By adjusting the servo motor's rotation angles, HydroSignal ensures effective and intuitive visualization of dual parameters like soil moisture and temperature. This approach not only increases the platform's applicability in environmental monitoring but also emphasizes its flexibility in presenting complex data in a comprehensible manner, catering different monitoring requirements and scenarios.

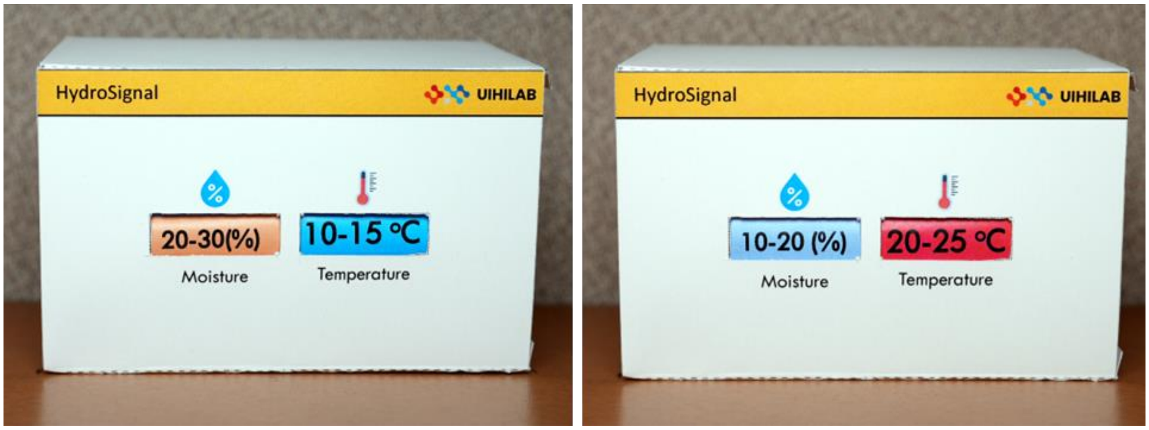


Figure 15. Real-time monitoring of soil moisture and temperature data from IFIS service for Iowa City, IA.

3.5. Discussions

This study has introduced HydroSignal, a novel, cost-effective, and open-source IoT-based hydrological monitoring platform that uniquely combines hardware, software, and innovative visualization designs. This enables users to easily access and manipulate data on various hydrological parameters collected from real-world sensors, all without requiring specialized knowledge in electronics. The platform’s user-friendly design and its emphasis on active visualization components make it an innovative tool in hydrological monitoring. The findings from this study highlight the potential for expansive future developments in applications, research, and education.

For educational purposes, HydroSignal utilizes the simplicity of Arduino C to offer an immersive learning experience that covers software development and hardware interaction. Its open-source firmware code simplifies programming basics and fosters user engagement with device capabilities enhancement. Moreover, the platform enhances understanding of IoT device connectivity, especially Wi-Fi configurations, thereby bolstering users' skills in network management and web development.

In terms of technical training and skill development, HydroSignal provides practical experience with microprocessor-based IoT devices. Users learn about the functionalities of input and output pins, gaining essential knowledge for hardware component interfacing and control. The project also offers experience in controlling servo motors, which enhances understanding of physical computing and device automation within the IoT ecosystem. Introducing additional sensor types could broaden the platform's applicability to various environmental parameters, enhancing the dataset for educational and research purposes.

Additionally, integrating HydroSignal into K12 STEM education could offer hands-on learning experiences that connect students with real-world environmental science and engineering concepts. This integration supports interdisciplinary learning, merging STEM with environmental education through interactive projects. The platform's potential in enhancing K12 education underscores the importance of equipping students and teachers with the necessary skills to incorporate IoT and hydrological monitoring into their lessons, fostering a safe and supportive learning environment. Visualization and engagement advancements are key to HydroSignal's approach. The platform ensures hydrological information is easily understandable and actionable, particularly benefiting students by enabling the visualization of theoretical data from sensors, thereby deepening their understanding of water resource states and management.

HydroSignal also presents opportunities for outreach activities and community engagement. Featuring the platform in science fairs and competitions (i.e., hackathons) can inspire students to undertake their projects and experiments. By facilitating student involvement in community science projects, HydroSignal bridges the gap between education and practical environmental action, enabling students to contribute to monitoring and conserving local water resources. This engagement not only enhances creativity and problem-solving skills but also raises awareness of hydrological issues and the significance of water resource management.

4. Conclusions

In this study, we developed HydroSignal, a novel open source IoT framework equipped with both software and hardware components, designed to facilitate the visualization and monitoring of hydrological parameters. By introducing an open-source software and hardware bundle, we significantly lowered the barriers to implementation, offering a user-friendly configuration over a coding-based approach. HydroSignal has emerged as a pioneering platform in hydrological monitoring, markedly improving the accessibility, analysis, and visualization of hydrological data.

We presented four distinct use cases to demonstrate the versatility and potential of HydroSignal in environmental science and education. The first example illustrated time series data for monitoring water level data received from USGS remote service. Second, we provided a use case for monitoring the water quality through turbidity levels with IWQIS web service. In the third example, we visualized flood alert visualization based on data from NWS. Finally, we demonstrated multi-variable monitoring of soil moisture and temperature data from IFIS. These are only a few use cases to illustrate the platform's broad applicability, and its profound impact on promoting environmental awareness, facilitating data-driven decision-making, and enhancing educational engagement through immersive learning experiences. Additionally, HydroSignal can integrate a wide range of environmental, agricultural, meteorological, and water quality data from corresponding remote service providers, further expanding its utility.

Looking to the future, HydroSignal is set for expansion into domains beyond hydrological monitoring, such as agriculture and urban planning, where IoT technology can offer invaluable insights. Future versions of the platform will feature advanced data analytics and machine learning to improve predictive capabilities, providing more sophisticated tools for environmental management and disaster communication. We also plan to broaden community engagement through citizen science projects, fostering greater public involvement in environmental conservation. Educational endeavors will be enhanced by developing modules that integrate HydroSignal into STEM curricula, offering students practical, real-world applications of hydrology and environmental science. With ongoing technological advancements in IoT and web development, HydroSignal is poised to remain at the cutting edge of environmental monitoring solutions, serving as a dynamic platform for researchers, educators, and the wider community.

Hackathon and online competitions with dedicated themes for HydroSignal platform can be organized annually. This is aimed at expanding our HydroSignal platform with more students and users. Dedicated prizes will stimulate innovative use cases and wider adoption of the platform. Moreover, Kaggle-style online competitions can be organized and open the framework to a national audience, challenging participants to find novel use cases and designs of HydroSignal platform for environmental data visualization.

The visual design element is a critical aspect of the HydroSignal platform. Tailoring an optimal visual design to the specific data being monitored not only improves understanding but also allows for deeper interpretation of the data. The ability to make complex data both accessible and visually appealing depends on the integration of aesthetics and functionality—the synergy of engineering, art, and design. Therefore, this project goes beyond just the technical execution of data visualization. It embodies a comprehensive approach that combines scientific sensitivity with artistic expression and design principles. It also underscores the importance of interdisciplinary collaboration in developing solutions that are visually stunning as well as technically sound.

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