Proof of concept: local precipitation-dependent rainwater management with smart water tanks

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Abstract: The effects of extreme weather events are increasingly having a negative impact on the water and wastewater infrastructure. Due to increasing land sealing in urban areas and more intense rain events, new concepts are needed to relieve the water and wastewater infrastructure. One possible approach is the usage of private rain storage as retention volume without negatively affecting the owner. Therefore, a smart approach is used to manage the rain storage in a situational way. This paper therefore presents a first prototype of a smart water tank, which was used to cover and test initial requirements. The goal was to develop an operational and portable hardware and software prototype early in the project.

Keywords: water management; smart water tank; heavy rainfalls; prototyping

1 Motivation

Climate change is the greatest challenges of our time. According to the IPCC Climate Report 2021 [Ma21], climate change continues to increase. It can be observed that future greenhouse emissions will intensify climate change. The consequence is the occurrence of increasing weather extremes [Ma21]. One of these weather extremes is heavy rain. It is characterized by short but intense precipitation and usually occurs locally. Due to this characteristic, heavy rain can lead to temporary overloading of wastewater infrastructure. As a result, flooding may occur in the affected areas. These weather extremes represent a challenge for water management utilities [FKB20].

Due to the sealed surface in urban areas, stormwater must be drained through the sewer system, as fewer natural areas are available for natural infiltration. If the sewer infrastructure is overloaded, flooding will inevitably occur. Because of these conditions, heavy rainfall is a serious problem in urban areas [PS17].

The Oldenburgisch-Ostfriesischer Wasserverband (OOWV) is the largest area supplier of drinking water in Germany. The OOWV provides drinking water and management of wastewater in the association's area [FKB20]. The OOWV addresses the problem of extreme weather events, which is intensified by climate change. As a water utility, the OOWV has an

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interest in working on solutions that mitigate the potential negative impacts of rain events. In various projects (e. g. [Öz20],[Ve23]) on blue and green infrastructure, the OOWV is researching possible integrative approaches for solutions. In the LEADER-funded project SWaT -Smart Water tank [Ve23], an smart water tank for private households is being developed. The prototype supports the Leader funded project of the OOWV and serves as an initial proof-of-concept, allowing the project team to provide more precise requirements to the assigned service provider and validate initial hypotheses and assumptions.

The idea follows the approach of storing and releasing rainwater in a controlled manner and thus generating decentralized retention volume. This is to be done by utilizing a smart water tank. An intelligent or smart water tank is characterized by additional features that set it apart from a conventional water tank. As a smart device, is able to network with other devices or services. It can also act context-sensitively by capturing data from the environment and acting autonomously [SRS18]. A smart water tank can dispense its contents manually or automatically, for example, by incoming data about heavy rainfalls. It is then refilled during the rainfall. In this way, it reduces the amount of rainwater that must be discharged from the wastewater infrastructure during heavy rainfall. The stored rainwater can be used afterwards locally for gardening. In theory, the intelligent control of the smart water tank does not create any disadvantage for the owner, as ideally, their collected is refilled after the rain event. The intelligent water tank requires other components besides the obligatory water tank. A controllable pump, valve or similar is needed to drain water. Sensors are also required to determine the fill level. The intelligent water tank is controlled by a microcontroller including software. Both the source code for the app and for the controller will be released as open source. Supplementary documents, including assembly instructions and a shopping list, will be provided alongside the source code.

This is how the presented smart water tank differentiates itself from other smart water tanks available on the market through three key aspects:

- Due to the release of the source code, it can be built by interested citizens
- The controller includes an algorithm that explicitly conditions the water discharge from the storage based on predicted precipitation. Other smart water tanks are not designed for this since they only focus on the interests of a single owner and do not address infrastructure relief
- The smart water tank can access an interface for forecasting (heavy) rainfall events. Other smart water tanks generally do not incorporate this information

To ensure a systematic approach during development, interviews were conducted with experts and potential users. From the analysis, functional and non-functional requirements for the prototype were collected. In addition, research was conducted on existing intelligent rainwater storage systems. Based on this information and requirements, an implementation concept was created. The implementation included both the construction of a prototype from the components determined in the concept and the development of software to control this prototype. The prototype was then evaluated against the requirements, which included a workshop and a field test at a public event and feedback from interested citizens.

1.1 Smart Water Tanks

In the market for smart water tanks, there are various solutions. There are providers that offer a variety of compatible products in a sort of modular system. An individual complete system consisting of a tank, filter, pumps, and water management system can be assembled from this modular system. Additionally, there are providers of retrofit systems that make an existing tank intelligent and sometimes even controllable. Some of these providers offer a modular system to network multiple tanks, among other things. Finally, a Do It Yourself (DIY) project is presented. This project describes the construction of a smart water tank and the necessary components. As part of the market overview, a comparison was created that compares the functions, technical data, and other features of each system (see Table 1).

	UWO Water Combimat	Kingspan Smart Water Tank	MALL Tano L System	Kingspan Watchman Anywhere Pro	Kingspan Watchman SENSiT	Smart Water SW900	Davey Tank Sense	Water Vision
Smart Home Integration	Wi-Fi	Wi-Fi	Wi-Fi	No	Wi-Fi	Wi-Fi	No	Wi-Fi
Data Backup	Yes	Yes	No	Yes	Yes	Yes	Yes	No
App Availability	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Fill Level Display	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Consumption Display	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Consumption Prediction	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Weather Forecast	No	No	No	No	No	Yes	No	No
Alerts	No	Yes	No	Yes	Yes	Yes	Yes	Yes

Tab. 1: Comparison of different smart water tanks

UWO Water offers a modular system of tanks and rainwater management systems. They provide plastic and concrete underground tanks with varying capacities from 500 to 15,000 liters. The Combimat I 3/24 and II 3/25 rainwater management systems utilize a centrifugal pump to transfer rainwater from the tank to an intermediate storage, maintaining a certain level. The system can connect to WLAN networks, sending data like fill levels and modes to the manufacturer's server, accessible via a web application. Kingspan offers complete systems with tanks ranging from 2,000 to 22,400 liters. The system automatically switches to using tap water when the tank is empty. Users can monitor fill levels and consumption through an app, and the system predicts when the tank will be empty based on consumption history. Notifications are sent for low or rapidly dropping levels. MALL uses concrete cisterns buried underground, with capacities between 3,200 to 12,500 liters. Their rainwater management system includes a pump with dry-run protection and an intermediate storage that can be filled from the tap water network. An electronic fill level display can be integrated into home networks for remote access. This retrofit system employs an ultrasonic sensor to measure and transmit tank levels via an integrated SIM card over cellular networks. Users can access data through a web server or receive regular updates. The system predicts when the tank will be empty and sends notifications for low levels. Similar to the Watchman Anywhere Pro, this system utilizes a wireless transmission via a USB radio receiver. It offers remote monitoring through a smartphone app connected via Wi-Fi, and it can also be integrated with Amazon Alexa. SW900 system allows networking up to twelve tanks and pumps. Sensors measure water pressure to determine tank levels, with a wireless range of up to 10 kilometers. A smartphone app offers monitoring and control, including scheduling pump operations and displaying weather forecasts. The Tank Sense sensor uses a pressure sensor to measure levels and consumption. It connects to a smartphone app via Bluetooth Low Energy (BLE), which provides rain forecasts and low-level warnings. This system can network up to 16 tanks and 12 pumps via Wi-Fi. An app displays operation modes, fill levels, and estimated time until empty. Pumps can be scheduled, and leak alerts are sent through the app. The Sonar Sentry project involves constructing an intelligent water tank using components like an ultrasonic sensor and a microcontroller. The design and circuitry are explained, with a focus on connecting a water pump. The provided code supports the project.

2 Concept

As part of the concept, components need to be found for the development of an smart water tank. Since there is a huge number of possible components for the sensor and actuator components, as well as the microcontroller component, a preselection was made. Prior to the construction of the smart water tank, a circuit diagram was developed (fig. 1). This diagram represents the planned wiring of the components and their interfaces. Each of the large boxes represents an electrical component, which in turn contains smaller boxes. These smaller boxes represent the pins, interfaces, or connectors of the component. Generally, each box or smaller box is labeled. The red lines marked with a plus sign and the blue lines marked with a minus sign represent the power supply rails of the breadboard.

Furthermore, all the wishes and requirements mentioned by the interviewees regarding an intelligent water tank were compiled and visualized in a use case diagram. The use case diagram includes two stakeholder: the water utility and the private household of the smart water tank. The following use cases were captured:

- **View water level**: Both stakeholder want to view the current water level of the water tank.

- **Drain water from the tank**: Water Utility wants the ability to drain water from the tank when deemed necessary.
- **View measured system data**: Water Utility wants access to measured or stored data, such as water levels, to use for analysis and further research and refinement of the model
- **Extract water for personal use**: The user want to utilize the water stored in the tank for personal purposes
- **View consumption data**: The user desires an overview of how much water they have used
- **Warning for heavy rainfall**: Notification about heavy rainfall that could result in the tank being emptied.
- **Warning for sudden decrease in water levels**: The user also wished to be warned if, for example, the water level suddenly drops, as such events may indicate malfunctions.
- **Setup via QR code**: Simplified device setup using a QR code.
- **Tank configuration**: Advanced configuration options, particularly an adjustable reserve, to provide added value for interested users.

Using the circuit diagram, component analysis, use case diagram, and the idea of the

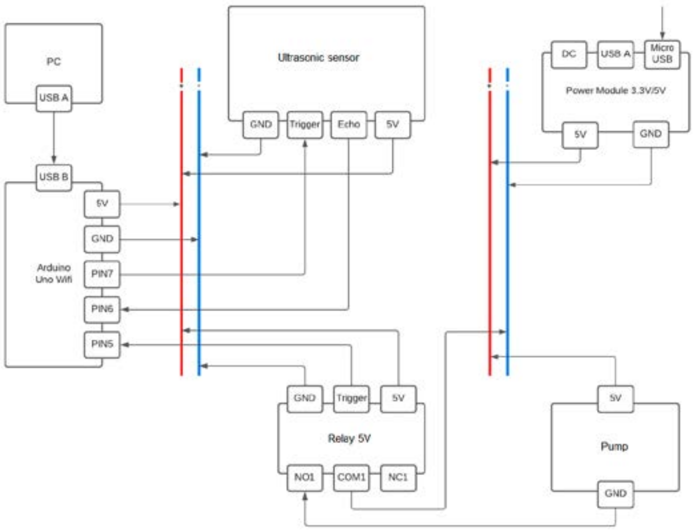

Abb. 1: Circuit diagram of the prototype with the different modules, sensors, and connections.

intelligent water tank described in the project proposal, the relevant requirements for a prototype were implemented. Therefore, expectations such as setup using QR codes were not included, as they are not highly relevant for a prototype. Instead, the focus was on aspects that are essential for the basic functionality of an intelligent water tank.

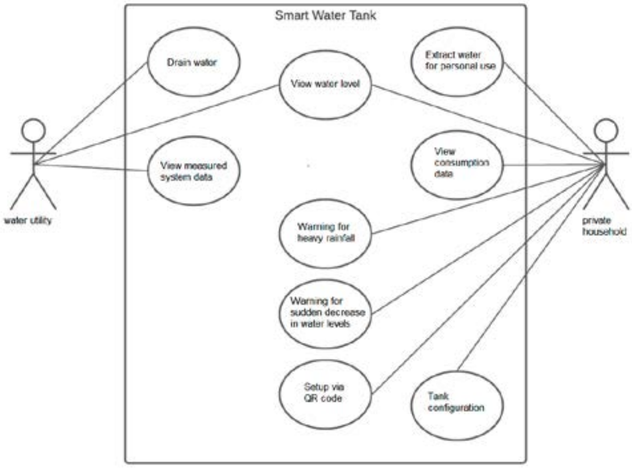

Abb. 2: Presentation of the identified use cases in a use case diagram with the stakeholders of private households and water providers.

3 Implementation

The development process followed an iterative approach. The goal of each iteration was the implementation of an additional function. Following the implementation of a function, the testing of that function and the entire system took place. The tests were conducted manually and focused not only on the software but also on the interaction with the hardware. Due to time constraints, test automation was not implemented.

The objective of the first version of the prototype was to realize the circuit diagram (see fig. 1) developed in the concept and to establish basic control of the sensors and actuators by the microcontroller. For the second version of the prototype, the designated components could now be used. Therefore, the focus for the second version was to establish a connection with a Wi-Fi network and implement a rudimentary interface for accessing the microcontroller through a web browser. The goal of the third version was to enable a graphical user interface through a web browser. The focus of the fourth version was to expand the capabilities of the user interface or web app. In this final fifth version, numerous bugs were fixed and minor enhancements were made. Figure 3 illustrates the development of the hardware prototype across the different versions.

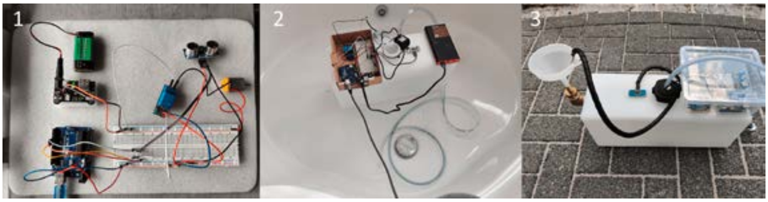

Abb. 3: Three out of five iteration steps of the prototype are shown. The left image shows the initial version of the prototype. The middle image shows an intermediate version, and the right image displays the final version of the prototype.

The core of the prototype consists of a rectangular 12 liter plastic water tank. On each of the narrow sides of the tank, there is a 3/4 inch thread, one located near the top and the other near the bottom. On the side with the upper thread, a funnel has been attached using several adapter pieces, an elbow fitting, and a tube connector. This funnel allows water to be poured into the tank. Additionally, the drip sensor is integrated into this funnel. To empty the tank when it is disconnected from power, a water tap has been screwed into the low-threaded side, allowing water to be drained.

The prototype's pump is installed inside the tank itself. This is due to the pump's suction power and its permeability to water. During testing, it was observed that when the pump was mounted on top of the water tank, it did not have enough force to draw water through a tube. Furthermore, water could flow through the pump even when it was turned off. To solve these two problems, the pump was directly glued under the lid into the tank. From there, a drain tube leads out through the lid. The ultrasonic sensor needs to be positioned in a way that it is directed downwards onto the tank bottom. For this purpose, two holes were drilled, matching the diameter and spacing of the ultrasonic transmitter and receiver on the sensor. This allows the ultrasonic sensor to be easily inserted from above into the tank.

Additionally, the tank has an overflow. A hole was drilled at the level of the ultrasonic sensor, in which a tube is inserted to redirect excess water. The remaining components of the prototype are installed in a plastic box. Holes and cutouts were made in the box to allow access to the connections of the microcontroller and power supply module from the outside, as well as to route cables for the pump, drip sensor, and ultrasonic sensor to the outside. This plastic box was glued to the top of the water tank. The circuit diagram of the concept has undergone minimal changes for the final prototype. The only difference is the connection of a 5-volt drip sensor. It is supplied with 5 volts via the breadboard's power rail, which is powered by the microcontroller. Additionally, it is connected to the analog pin.

3.1 App

The software implementation of the prototype was done using the Arduino IDE. The program was organized into multiple .ino files. In addition to the main file, which contains the setup

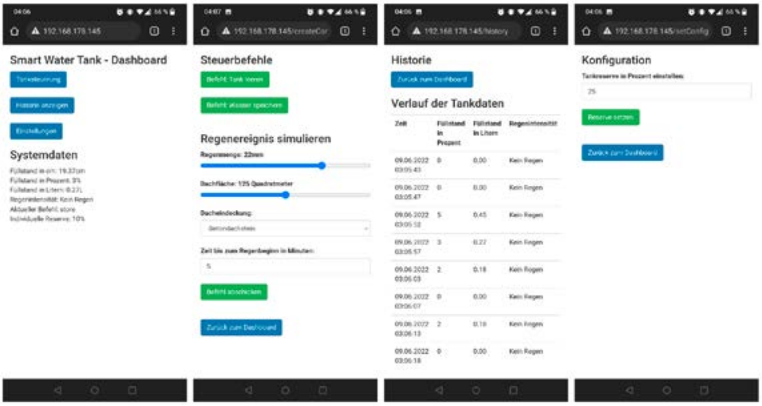

Abb. 4: Presentation of the web app for configuration, control, and display of historical data.

and loop methods, logical components such as methods for establishing a Wi-Fi connection were outsourced to separate .ino files. There are .ino files for the logical components: Wi-Fi connection, web server, rain logger, and control of the sensors and actuators. Furthermore, the program has a separate file where configurable variables are stored. However, the values of these variables must be determined at the latest during the compilation process. This includes the network name and password, the interval at which the rain logger stores data, the number of storage slots for the rain logger, and a conversion factor for converting simulated rainfall amounts to the prototype's tank volume. Before the compilation process, these additional .ino files are concatenated to the main file [Du20]. This organization into separate files with thematic relevance greatly improves the readability of the source code.

The following features have been implemented:

- **Filling Level Measurement:** The prototype is capable of measuring and monitoring the water level in the tank.
- **Web Server Handling:** The prototype includes functionality for handling web server operations, allowing users to access and interact with the tank's data through a web browser (figure 4).
- **Rainfall Event Calculation:** The prototype can simulate rainfall events based on the collected data, providing information about the amount and duration of rain.
- **Rain Logger Functionality:** The prototype includes a rain logger feature that records and stores data about rainfall events, allowing users to view and analyze the recorded information.

4 Evaluation

The concept for an intelligent water tank was created and implemented, and now it needs to be evaluated to determine the extent to which it has met the specified requirements. In the case of this prototype, many requirements can be directly assessed as either fulfilled or not fulfilled. These requirements typically describe functions or technical specifications that have either been implemented or not. Out of the original 14 functional requirements and nine non-functional requirements, all but three functional requirements have been met. All three unfulfilled requirements are non-mandatory. The reasons for not meeting these requirements primarily stem from the project's limited time frame. Additionally, the relatively imprecise water level sensor posed a challenge for implementing requirements to store the fill level and notify the user when a low, high, or suddenly decreasing fill levels, is detected by the system. Furthermore, a workshop was conducted with experts to verify the fulfillment of the requirements by gathering their feedback. The workshop can be roughly divided into the following sections:

Upon comparison, it is evident that there are similarities between the workshop participants' points and the identified requirements, such as displaying system data, but also many differences, including points like a quick return on investment, which are relevant for market-ready products. The next step involved describing the prototype's structure and presenting its key core functions. Additionally, all four pages of the web interface were introduced, and the controls and displays were explained. This was followed by a live demonstration, in which a majority of the prototype's functions were showcased. Subsequently, a discussion took place among all participants. During the discussion, the question arose as to whether the prototype fulfilled the requirements, what aspects were implemented well or less effectively, and what could be addressed differently or added in future developments. Overall, it can be concluded that the workshop participants considered the requirements for the prototype to be fulfilled. The user interface, history feature, and the controlled discharge of water during rain simulations were highlighted as positive aspects. However, the measurement of rainfall intensity using a droplet sensor was noted as a negative aspect. For future developments, it was suggested that a more accurate and reliable water level sensor would open up new possibilities, such as alternative methods for calculating rainfall intensity. Furthermore, the possibility of using a solenoid valve instead of a pump was discussed. Additionally, it was noted that the presence of a physical prototype contributed to the value of the discussion.

5 Outlook and future work

As mentioned in the evaluation, future developments of the intelligent water storage system may involve the use of different or new components to gather new data and improve the existing functionalities. Specifically, the use of a more accurate and reliab+le water level sensor, as well as the implementation of a solenoid valve instead of a pump, have been identified as potential improvements. These two components would be logical steps to further enhance the capabilities of the smart water storage system.

Furthermore, the current prototype already provides a solid foundation for connectivity. This aspect can be expanded upon to simplify and enhance access to the smart water tank. The introduction of a setup process could facilitate the transition from a prototype to a final product, improving user-friendliness and enabling seamless integration with existing systems. Additionally, features such as remote access, event notifications, or integration with smart home platforms could be considered to further expand the functionality of the smart water tank. Overall, there are numerous possibilities for further development and customization of the intelligent water storage system based on the existing prototype and to meet specific requirements and needs. Continuous improvement and the integration of new technologies can contribute to making the intelligent water storage system a robust and efficient product that provides real value to users.

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