Embedded Control System for Residential Heating, Cooling, and Ventilation

Szabolcs Schekk
Obuda University
Alba Regia Faculty
Székesfehéhérvár, Hungary
sschekk@stud.uni-obuda.hu

Bertalan Beszédes
Obuda University
Alba Regia Faculty
Székesfehérvár, Hungary
beszedes.bertalan@uni-obuda.hu
https://orcid.org/0000-0002-9350-1802

***Abstract*—This paper discusses the development of a universal controller designed for households equipped with modern HVAC technology. The controller's task is to optimize heating, cooling, and ventilation, as well as manage the Smart Grid functionality of heat pump systems. The paper presents the hardware and software solutions employed, and provides a detailed description of the system's operation and structure.**

***Keywords*— heating control, cooling control, ventilation control, smart grid, smart control system, residential heating, residential cooling, residential ventilation**

I. Introduction

In modern households, comfortable and energy-efficient climate control is essential. In this paper, we present the development of a universal controller designed to meet these needs. The controller aims to optimize heating, cooling, and ventilation, taking into account external temperatures, user preferences, and the current state of the energy provider's infrastructure via the SmartGrid [1, 2] system. Energy efficiency is achieved through appropriate weather compensating regulation, the advantage of which lies in reducing the temperature fluctuations and inertia losses associated with traditional thermostat systems. This can result in up to 10% energy and cost savings [3, 4].

In addition to energy efficiency benefits, ventilation regulation also has favorable physiological effects. Humans perceive indoor air quality primarily through smell and via the conjunctiva of the eyes. Poor air quality can lead to poisoning in severe cases, while prolonged exposure to lower quality air can cause irritation and promote the development of chronic respiratory diseases [5-7].

II. Materials and Methods

Residential heat pumps generally come with an internal changeover valve, which determines whether to produce hot water or heating water based on current needs, follow on Fig. 1. and check Fig. 2. The internal changeover valve directs the water flow accordingly towards hot water production or heating. The supplementary heating unit may not have an internal changeover valve, so external changeover valves are placed in the flow and return pipes. These operate in parallel with each other. Heating appliances have their own pumps. Check valves ensure that water circulates securely between heating circuits or storage tanks, without flowing through each other. The buffer tank functions as an energy storage unit [8].

When the controller determines that a sufficient amount of energy is available, it activates the buffer tank into the heating system by switching the changeover valve before the buffer tank. The hydraulic balancer ensures the necessary flow rate for the heat generator and heating circuit pumps without interfering with each other. A mixing valve control system consists of a pump, a mixing valve, and a forward water temperature sensor. Both the switching and mixing valves are three-way valves, but the difference is that the mixing valve can also be in an intermediate position, while the switching one only switches between the two end positions.

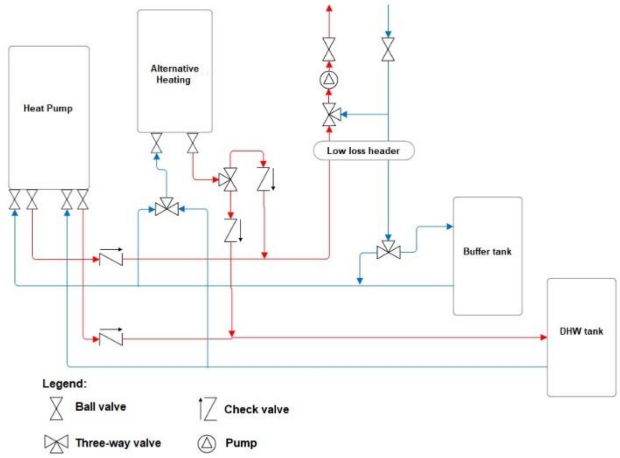

Figure 1: General hydraulic diagram of a residential heating system

Figure 2: A photograph of a heating center based of the diagram

For hardware design, selecting a suitable microcontroller with sufficient I/O ports, ADCs, and communication interfaces is essential. The Arduino UNO R4 WiFi [9, 10] card forms the basis of the control, with its built-in ESP32-S3 module enabling wireless communication. Standard heating appliances, pumps, and control valves can be used in the system. Heating appliances must have a standard thermostat input. This is a two-pole connector. To operate this thermostat input, a potential-free contact must be connected (see on Fig. 3. and Fig. 4.). The heating appliance pulls one pole of the input to a level it can interpret (usually 230 VAC), then expects the same voltage level back on its other pole. The closed position of the contact indicates the need for heating.

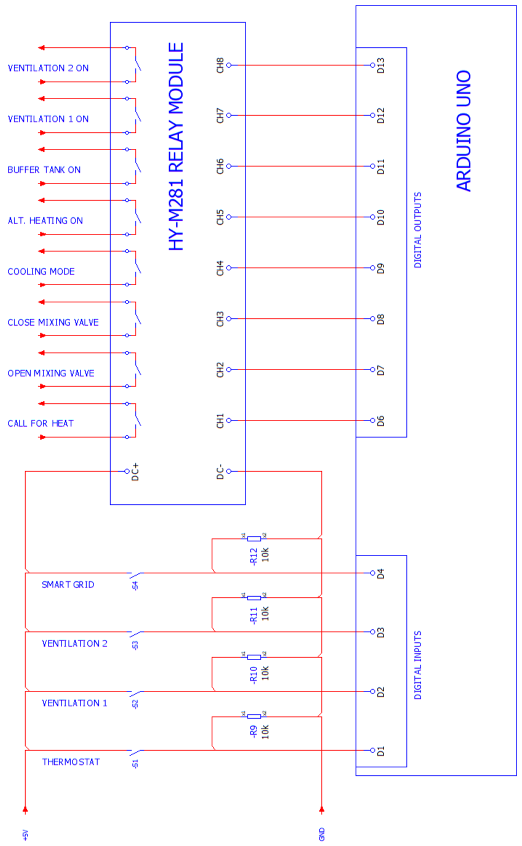

Figure 3.: Allocation of digital inputs and outputs of the controller

All standard household pumps are compatible with the device. A single-phase pump can be controlled through the controller up to 2 Amps, but it is recommended to isolate the pumps with relays or contactors as a solution. In this case, we certainly do not overload the output of the controller, and even a three-phase pump can be connected, or in the case of a single-phase pump, we can also disconnect the neutral wire.

This is a common practice in boiler rooms or particularly humid, moist rooms. Any type of changeover valve can be applied as well. In the case of a spring-return design, direct control from the controller is possible, otherwise, relay isolation is required for switching between the opening and closing directions. Only a stepper-type design can be used for the mixing valve since the controller controls the valve with a digital signal. For analog control mixing valves (0-10 V, 4-20 mA), additional accessories are required.

The temperature sensors should be of the Pt1000 type. Instead of resistance thermometers, we could have used thermocouples or standard temperature transmitters. We chose Pt1000 for its reliability, favorable price, and widespread availability [11, 12].

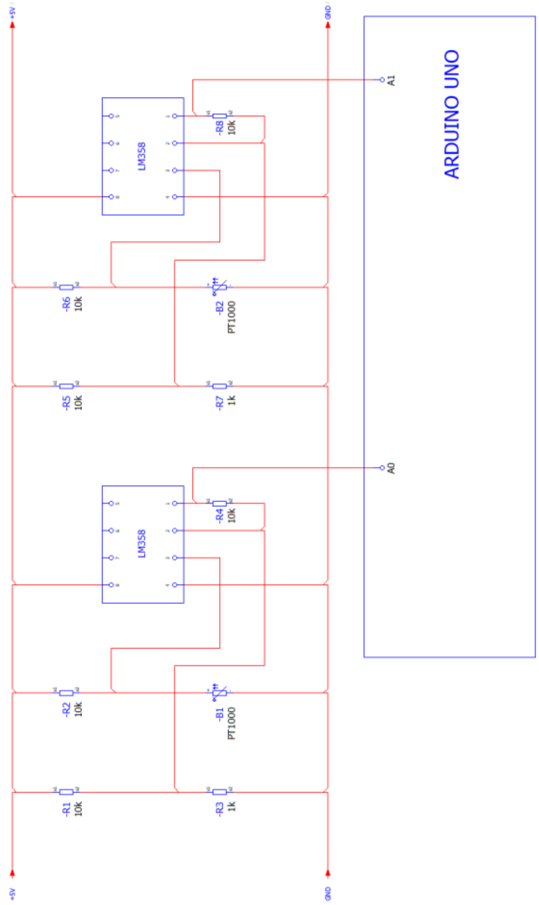

Figure 4: Temperature sensing by the controller

III. Results

The developed controller successfully manages the functions of heating, cooling, and ventilation, taking into account external environmental conditions, user preferences, and energy provider system status indicators (see on Fig. 5. and Fig. 6.). The system ensures stable operation and ensures user-friendly interface.

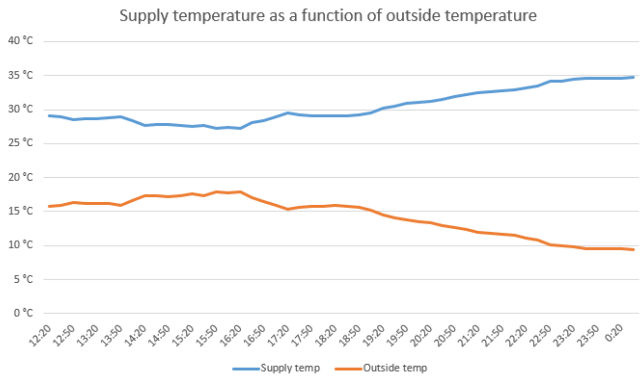

Figure 5: Graph of the measured temperature values during the operation of the controller

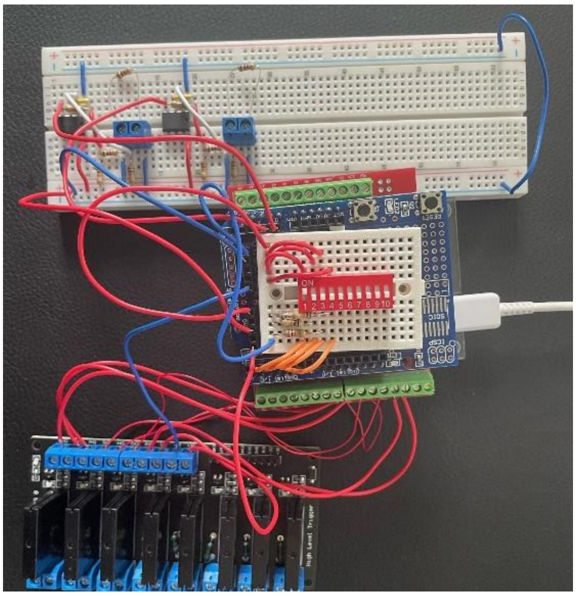

Figure 6: Controller subsystems and operation

Creating an embedded control system for residential heating, cooling, and ventilation involves designing both the hardware and software components to ensure efficient and reliable operation [13, 14]. With different sensors and actuators, it is a multiple input and multiple output system, therefore various control methods can be used [15-17]. In subprocesses control algorithms such as PID control is used for keeping up the desired technological levels. Sensor data processing subroutines includes filtering techniques to remove noise and calibration routines for accuracy [18-20].

The comprehensive software state diagram can be seen on Fig. 7. and the firmware implementation can be seen on Fig. 8. Besides that, the system contains communication interfaces and handles the user interface. Additionally, energy optimization algorithms [21-23] are incorporating to enable energy-efficient operation, adjusting scheduling and setpoints based on occupancy and external weather conditions [24-26].

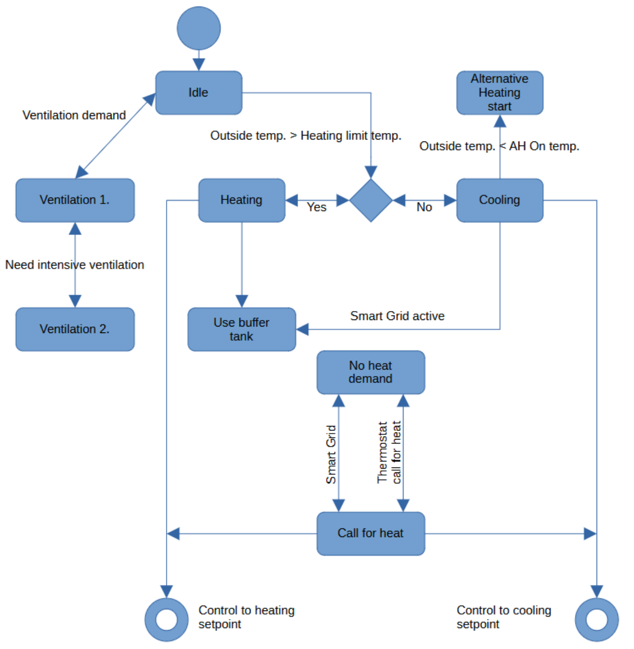

Figure 7: Controller state diagram

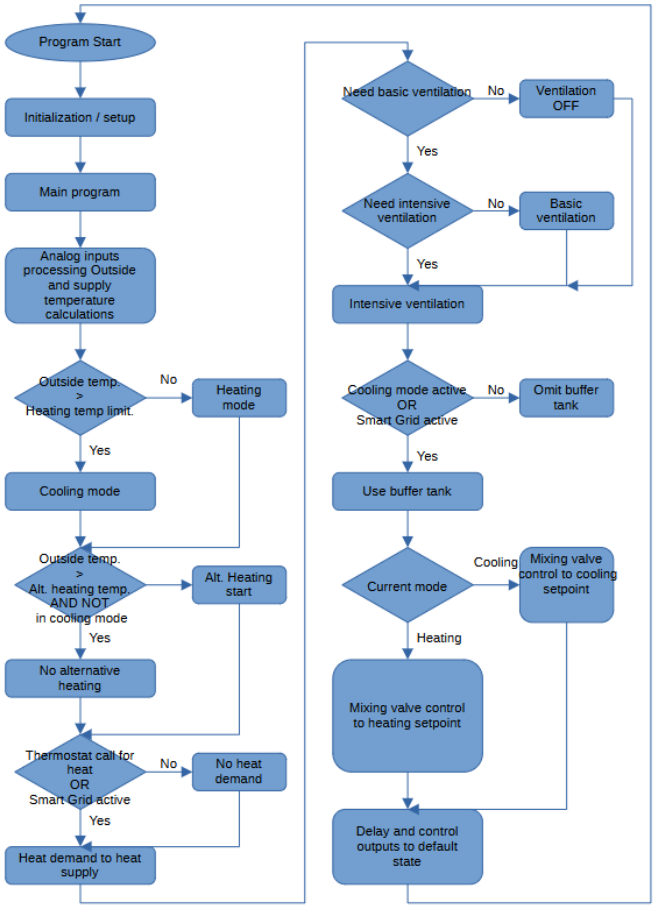

Figure 8: Controller program flowchart

Further optimization of code for efficiency, responsiveness and fine-tuning control algorithms for optimal performance are necessary in each different application before final deployment. Fors maintenance and updates for firmware and software can be done via the open source development environment, also monitoring and diagnostics, and implementing alert systems for faults and maintenance needs will help maintain system reliability and efficiency.

In the context of an embedded control system for residential climatization, effective data collection and secure data management are crucial for optimizing performance and ensuring user safety. The integration of data collection methodologies, as discussed in [27] highlights the significance of using geographic information systems for gathering environmental data in residential settings. The framework facilitates real-time data integration, allowing for a comprehensive understanding of the spatial and temporal dynamics of residential energy use, ultimately contributing to improved system efficiency. [28] also emphasize the importance of secure data storage and transmission within such embedded systems. As residential environments increasingly rely on interconnected devices, ensuring the security of sensitive data becomes paramount. Implementing robust encryption protocols and secure communication channels will safeguard user information and prevent unauthorized access. The combined insights from both publications underscore the necessity of a holistic approach to data management, where efficient data collection techniques are complemented by stringent security measures.

IV. CONCLUSION

The presented embedded control system for residential heating, cooling, and ventilation involves integrating various sensors and actuators with a microcontroller, developing control algorithms, and ensuring a user-friendly interface. It has resulted in an efficient and flexible system capable of meeting the climate control needs of modern households. The system in focusing on maintaining comfort, ensuring air quality, and optimizing energy consumption. The technologies and solutions employed in the development allow for future enhancements and optimizations to be implemented.

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