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DEVELOPMENT AND EXPERIMENTAL RESEARCH OF A SYSTEM WITH ESP32 FOR REGISTRATION AND ANALYSIS OF ULTRASOUND ECHO SIGNALS

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Summary
The presented hardware-software system is based on an ESP32 microcontroller for recording and analyzing ultrasonic echo signals in non-contact testing of materials. The goal is to develop an experimental platform for recording raw (RAW) signals and evaluating factors affecting their digital representation. The system uses the analog signal output from the HC-SR04 ultrasonic module. Embedded software and a computer application have been developed to process measurement data. Functions include recording, transmission, visualization and data storage. Diagnostic processing includes DC offset correction, time alignment and extraction of amplitude and shape features. Initial measurements show changes in the echo signal when changing the connection to the measurement input. This requires checking the matching of the input signal and the reliability of its recorded shape. After this check, the extracted features will be used to study the characteristics of the materials. The scientific and technical contribution consists in the implementation and initial functional verification of the platform for recording and processing signals. A method for systematic measurement validation is also proposed. The obtained results show the limitations of the current configuration and directions for its improvement, while reliable material recognition remains the subject of future experimental validation.

Keywords: ESP32; ultrasonic echo signals; data logging; digital signal processing; non-contact testing.

1. INTRODUCTION AND PURPOSE

The HC-SR04 ultrasonic module is commonly used for distance measurement and is one of the most popular distance measurement sensors in various projects. It is easy to integrate and offers good measurement accuracy, with its standard ECHO output providing a digital pulse from which the distance to an object can be calculated. The measured analog signal contains additional information, including variations in its amplitude, duration, and shape. Examining these and other additional characteristics can help distinguish reflected signals from different objects. The results obtained may also depend on the measurement conditions and the electronic circuit.

Various studies have examined the use of ultrasonic measurements in combination with digital signal processing and machine learning for industrial process monitoring and object evaluation [1, 2]. Other publications describe studies on material classification, defect detection and object recognition using ultrasonic reflections [3–5]. All these studies provide a basis for analyzing the shape of the echo signal. The results described, obtained with other systems, cannot be automatically assumed to be valid when using the HC-SR04 module.

In the developed experimental system, the analog signal is output from the HC-SR04 module and fed to the analog input of the ESP32. In the initial experiments, changes in the echo signal were observed when the connection to the measurement input was changed. This raises the question of the influence of the entire measurement recording scheme on the recorded waveform. Before proceeding to compare different materials, it is necessary to investigate the input range of the ADC, possible signal distortions and repeatability of the measurements.

The aim of this work is to develop and investigate a system for recording, visualizing and processing ultrasonic echo signals using an ESP32 microcontroller. The

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article describes the hardware connections, embedded software, computer application and basic signal processing operations. The present study is aimed at verifying the functional performance of the system and the limitations established during preliminary measurements. Reliable material recognition will require additional experiments and independent validation.

2. SYSTEM ARCHITECTURE

The system considered here is built on the basis of the widely used ESP32-WROOM-32E microcontroller module [6] and the HC-SR04 ultrasonic module. In addition to the standard TRIG and ECHO connections and selected GPIO pins for peripheral devices, an analog RAW signal is output from the receiving path of the ultrasonic module, before the comparator. Thanks to this modification, direct access to the echo signal shape is provided, which cannot be obtained from the standard digital output for distance measurement.

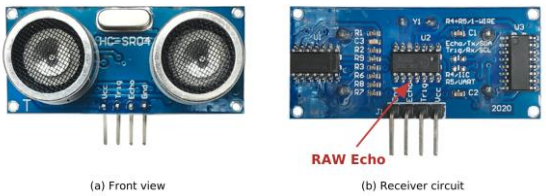


Fig. 1. *Echo signal output point indicated*

A local interface of the system has been developed, which includes a TFT display with an ST7735 controller and two touch buttons. The AHT10 sensor measures the temperature and relative humidity of the air, and the BMP180 measures the atmospheric pressure. The measured environmental parameters are visualized on the display, and the temperature and humidity are also used in the software calculation of the speed of sound.

The TRIG and ECHO pins of the ultrasonic module are connected to GPIO5 and GPIO18 of the ESP32, respectively, and the RAW analog signal is fed to GPIO34. The two touch buttons connected to GPIO27 and GPIO26 are used to control the menu on the TFT display and the entire measurement process. The AHT10 and BMP180 sensors are connected to a common I²C communication bus, as shown in Fig. 2.

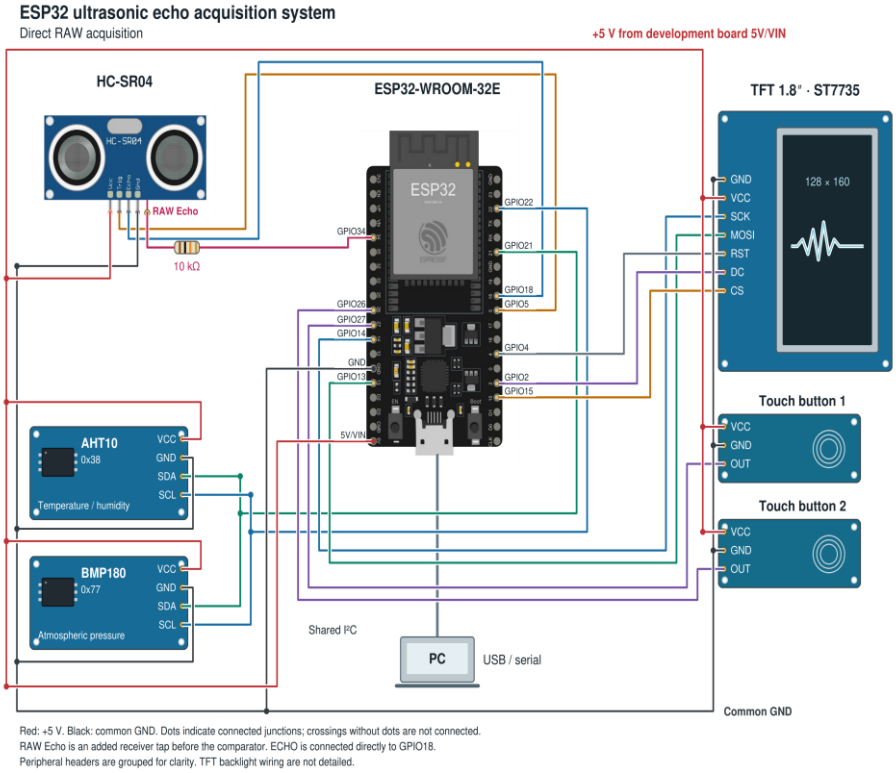


Fig. 2. *Experimental circuit diagram for direct recording of the RAW signal and connections to the ESP32.*

The implemented measurement system is studied in two configurations. In the first, the RAW signal is fed directly to the analog input GPIO34 of the ESP32 through a series-connected resistor with a resistance of 10 kΩ (Fig. 2). In the second configuration, the signal passes through an LM358 amplifier (Fig. 3). In this case, the 10 kΩ resistor is connected between the RAW output of the HC-SR04 and the input of the LM358 amplifier. The supply voltage used is 5 V.

An oscilloscope was used to track the received signals, allowing detailed observation and analysis of their shape. Channel CH2 measures the signal immediately after the RAW Echo output point, before the resistor, and channel CH1 measures the output signal of the amplifier before the GPIO34 input. The considered measurements of the RAW signal are performed without an amplifier and without additional DC offset voltage. The two configurations represent separate experiments.

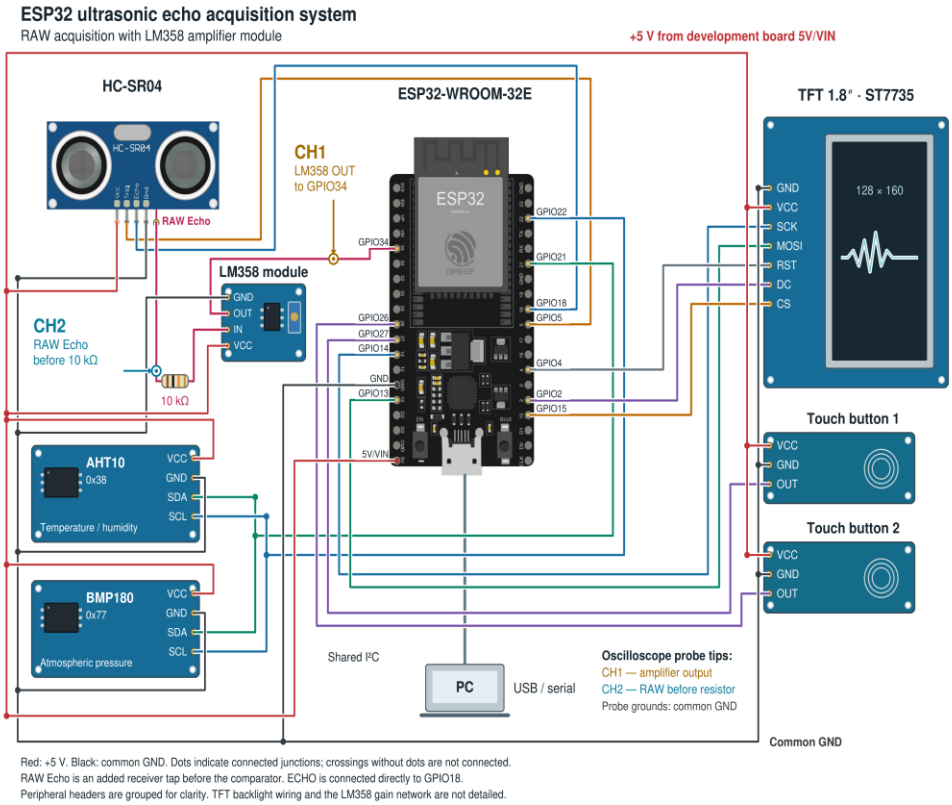


Fig. 3. *Experimental circuit diagram with LM358 amplifier and connection points of channels CH1 and CH2.*

3. SOFTWARE IMPLEMENTATION AND SYSTEM OPERATION

The developed ESP32 software controls the measurement process, registers the echo signal and processes the received data, which are visualized on the TFT display. The data is also transmitted to the computer application. The analog signal, which is supplied to GPIO34, is sampled by the built-in analog-to-digital converter (ADC) of the microcontroller. In this process, the analog voltage is converted into a sequence of numerical values. The I²S peripheral module serves the data stream received from the ADC, and direct memory access (DMA) ensures their transfer to a buffer in the random access memory (RAM). In this way, the processor's involvement in the transfer of individual measured samples is reduced.

The samples received are grouped into measurement frames for subsequent processing and transmission. The ADC is configured with 12-bit resolution. The system supports nominal sampling rates of approximately 83, 160, 250 and 500 kHz, which can be selected via the PC application.

In the measurements considered, a nominal sampling rate of 250 kHz and 512 samples per frame were used. This corresponds to a nominal sample interval of 4 μs and a time window of 2.048 ms. The specified configuration parameters do not eliminate the need for experimental verification of the actual sampling rate and calibration of the ADC [7].



Fig. 4. Diagnostic interface of the PC application when measuring a sample at 15 cm. UNKNOWN denotes the experimental mode, not the recognition result.

The computer application is developed in the Python programming language with a graphical interface implemented using PyQt5. It allows you to select the sampling frequency and visualize the RAW signal, its envelope, filtered representation and the frequency spectrum calculated using the Fast Fourier Transform (FFT). The obtained and calculated signal characteristics can be viewed and analyzed, and the measurement results can be stored in CSV format files. Data exchange between the ESP32 and the computer application is carried out via a serial interface with a speed of 921600 baud. The measurement frame hold function allows the selected signal to be viewed in detail and analyzed with the available filters and tools. The material of the tested sample is set by the operator as a label and is viewed separately from the classifier result.

Working with the system involves setting the necessary measurement settings, starting the signal recording and then viewing or saving the results. The system supports the collection of reference measurement records and classification procedures. In the experimental mode used, the UNKNOWN indication, shown in Fig. 4, means that no material recognition result is output. The sample label, the distance to it and the measurement series settings are stored together with the records.

4. DATA REGISTRATION AND PROCESSING

All processing is performed on the registered RAW frame, with the resulting digital values being converted into echo signal characteristics by the developed software. The processing sequence includes DC offset removal, signal envelope extraction, time alignment and feature calculation.

In the measurement process, the constant offset is estimated from the initial part of the measurement frame and subtracted from the

recorded signal. Then, the envelope is extracted, which describes the variation of the echo signal amplitude over time. The time alignment used establishes a common reference point for comparing the individual measurement records. Thus, small differences in the echo arrival time are not directly interpreted as differences in the signal shape [8].

The amplitude characteristics are calculated from the time-aligned portion of the signal, and after normalization, the features describing its shape are determined. In the diagnostic mode considered, these calculations are performed by the ESP32. The capabilities of the microcontroller allow the amplitude and normalized representation to be used to separately study the strength and shape of the echo signal. However, normalization cannot restore information lost due to signal clipping or incorrect registration.

The presented measurement system confirms the functional performance of data recording and diagnostic processing but does not represent a quantitative validation of material recognition. In the PC application interface in Fig. 4, a signal clipping is reported at the lower limit of the input range. Therefore, the presented measurement record cannot serve as evidence of recording an undistorted echo signal shape, and the obtained amplitude and shape features should be interpreted with caution. Before evaluating the efficiency of the classifier, it is necessary to calibrate the ADC and assess the reliability of the recorded signal shape and the repeatability of the measurements.

5. DIRECTIONS FOR FUTURE DEVELOPMENT

5.1 VALIDATION OF THE MEASUREMENT TRACT

The next stage of development will be aimed at verifying the reliability of the recorded RAW signal. Initially, we will investigate the influence of connecting to GPIO34, then we will check the usable input range of the ADC, its linearity, and its behavior near the lower conversion limit [7].

We plan to perform oscilloscope measurements under identical conditions, which we will compare with the ESP32 recordings. This way, we will be able to distinguish changes in the analog measurement path from possible distortions during digital conversion. We will also check the actual sampling rate and the duration of the measurement window and signal amplification. The main criterion for choosing a configuration will be to preserve the echo shape with an acceptable noise level and without limiting the amplitude.

5.2 DATA AND REPEATABILITY

For future experiments, we plan to create a set of labeled measurement data for different materials. The computer application will allow organizing the records into groups of samples. For each record, the sample identifier, distance, orientation, measurement settings, and session information will be stored.

Repeatability will be assessed by the mean, standard deviation and, where applicable, the coefficient of variation of the calculated features. For this purpose, we will use individual actual measurement frames, rather than multiple readings of a signal held on the screen.

The measurements will be repeated after changing the distance, orientation, and position of the samples. We will also include different physical samples of the same material to verify that the system distinguishes the material and not just the specific object.

Amplitude and shape features will be analyzed separately and together. We will compare the differences between materials with the variability of measurements within a group. We will select the features that show the best stability and discrimination when changing measurement conditions.

5.3 ARTIFICIAL INTELLIGENCE FOR RECOGNITION

After confirming the reliability and

repeatability of the measurements, we will proceed to explore machine learning algorithms. We will initially compare the k-nearest neighbors (k-NN) method and support vector machines (SVM) [9]. If there is enough diverse data, we will also consider a neural network that uses the envelope or temporal representation of the echo signal.

A similar approach for training on ultrasonic echo signals has been presented for hand gesture recognition [10]. However, these results do not prove the applicability of the method for material recognition with our system.

The training, tuning and final test data will be divided by measurement sessions and repositioning, and if there are enough samples, by physical objects. Feature selection will be performed without using the test data. The evaluation will include a confusion matrix, indicators for each material and the possibility of rejecting classification in case of insufficiently reliable signal.

Initial training will be done on a computer. After assessing the accuracy, memory requirements, and processing time, we will evaluate the feasibility of implementing the selected model on the ESP32. If its resources prove insufficient, we will consider using a newer microcontroller.

6. CONCLUSION

A platform based on ESP32 and HC-SR04 for recording and processing of analog ultrasonic echo signals has been developed and implemented. The described system combines signal recording, visualization on a TFT display and via a PC application, serial communication, storage of measurements and extraction of diagnostic features. The main contribution of the present work is the initial functional validation of the developed platform. The presented system does not establish either metrologically confirmed accuracy of signal shape reproduction or accuracy of material classification.

Reliable material recognition remains a task for subsequent experimental validation. The quality of the registered signal, the repeatability of the extracted features and their sensitivity to the measurement geometry and environmental conditions are to be assessed. After this stage, sufficiently representative sets of measurement data will be collected, and different machine learning methods will be compared through independent testing. This approach will allow us to assess both the capabilities and limitations of the developed system. If necessary, existing hardware may be replaced or new hardware added to the already developed configuration. After confirming its robustness under different measurement conditions, the platform can be further developed for contactless discrimination of a limited set of materials under certain conditions, as well as for autonomous data processing directly in the microcontroller.

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