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Application of the ESP32 microcontroller and FDM technology in the development of an electrotechnical harness connection tester

Abstract

The article describes the design and construction of a prototype device for testing electrical harness connections. The tester combines the functionality of the ESP32 microcontroller with the flexibility of additive manufacturing technology used in the FDM method. A specialized PCB board was created in KiCAD, which integrates the ESP32 with input and output expanders, while the housing and mechanical components were manufactured using 3D printing technology. The software, written in C++, runs in the Arduino environment, allowing for intuitive operation of the device using a 2.8-inch touch screen and configuration files stored on an SD card. Functional tests confirmed that the device is capable of testing sixty-four wire connections, proving its practical application. A cost analysis showed that the total expenditure on the prototype was approximately PLN 770, which is significantly lower than commercial testers available on the market. The results of the research indicate that the combination of microcontrollers and 3D printing is an innovative and cost-effective solution for small and medium-sized companies.

Keywords: Additive manufacturing, FDM 3D printing, ESP32 microcontroller, Wire harness tester, PCB design, Prototyping, Touchscreen interface, Low-cost instrumentation.

Zastosowanie mikrokontrolera ESP32 i technologii FDM w budowie testera połączeń wiązek elektrotechnicznych

Streszczenie

Artykuł opisuje projekt oraz budowę prototypu urządzenia przeznaczonego do testowania połączeń wiązek elektrycznych. Tester łączy w sobie funkcjonalność mikrokontrolera ESP32 oraz elastyczność technologii przyrostowych stosowanej w metodzie FDM. Stworzono specjalistyczną płytkę PCB w programie KiCAD, która integruje ESP32 wraz z ekspanderami wejść i wyjść, natomiast obudowa i elementy mechaniczne zostały wyprodukowane w technologii druku 3D. Oprogramowanie napisane w języku C++ działa w środowisku Arduino, co pozwala na intuicyjną obsługę urządzenia przy użyciu 2,8-calowego ekranu dotykowego oraz plików konfiguracyjnych przechowywanych na karcie SD. Testy funkcjonalne potwierdziły, że urządzenie jest w stanie sprawdzić 64 połączenia przewodów, co dowodzi jego praktycznego zastosowania. Analiza kosztów wykazała, że całkowity wydatek na prototyp wyniósł około 770 zł, co jest kwotą znacznie niższą w porównaniu do komercyjnych testerów dostępnych na rynku. Wyniki badań wskazują, że połączenie mikrokontrolerów z drukowaniem 3D stanowi nowatorskie oraz kosztowo efektywne rozwiązanie dla małych i średnich firm.

Słowa kluczowe: wytwarzanie przyrostowe, druk 3D FDM, mikrokontroler ESP32, tester wiązek elektrotechnicznych, projektowanie PCB, prototypowanie, interfejs dotykowy, niskokosztowa aparatura pomiarowa.

1. Introduction

1.1. Importance of additive manufacturing in engineering

Additive technologies, commonly referred to as 3D printing, have become a key achievement in modern engineering and manufacturing. Their ability to produce components layer by layer allows for efficient prototyping, small-scale serial production, and flexible design adaptation (Gibson et al., 2021; Ngo et al., 2018). The use of 3D printing continues to evolve, ranging from the aerospace and automotive industries to medicine and consumer goods manufacturing.

One of the most important benefits of additive technologies is a significant reduction in product development time. Engineers can go from a digital design to a physical prototype in just a few hours, making this method the foundation of rapid prototyping and supporting innovation in various industries (Shahrubudin et al., 2019; Naghshineh, 2025).

Additive technologies also offer both environmental and economic benefits. Unlike subtractive methods, they produce significantly less waste, require less material, and in some cases also less energy. For this reason, 3D printing is seen as a technology that promotes sustainable development and reduces the negative environmental impact of manufacturing processes (Frazier, 2014; Shah, 2024; Javaid, 2021).

All these features mean that additive technologies are no longer considered a niche solution but are an integral part of modern engineering. Their growing importance reflects general trends in industry, where flexibility, cost-effectiveness, and sustainability play a key role.

1.2. FDM technology in prototyping

Among the various additive manufacturing methods, Fused Deposition Modeling (FDM) stands out as one of the most used techniques, primarily due to its low cost, ease of use, and the wide availability of printers on the market. FDM printers enable the creation of durable prototypes and functional parts directly from thermoplastic materials such as PLA, ABS, or PET-G (Bochnia, Kozior, 2024; Siemiński, Budzik, 2015). This technology has become a valuable tool for engineers and researchers in the design of enclosures, holders, and test equipment.

The popularity of FDM stems not only from the low cost of purchasing equipment and materials, but also from the wide selection of filaments available for processing. In addition to basic materials such as PLA and ABS, modern printers also support engineering materials, including polycarbonate (PC), polyamide (PA, nylon), and thermoplastic elastomers such as TPU, which significantly expand the industrial applications of this technology (Zhang et al., 2025). The literature also highlights the use of carbon fiber composites, which increase the stiffness and mechanical strength of prints (Budzik, 2013).

Despite its numerous advantages, FDM technology has its limitations. These include relatively low printing speed, anisotropy of mechanical properties resulting from the layered structure of the model, and visible layer lines on the surface, which can negatively affect the aesthetics and precision of the manufactured elements (Ngo et al., 2018). In addition, dimensional precision in FDM is lower than in resin-based technologies such as SLA or DLP (Zieliński, 2022).

Despite these limitations, due to its low cost, flexibility, and ease of access, FDM remains the most popular 3D printing technology. It is used not only in rapid prototyping and education, but also in low-volume production and even in the manufacture of end-use parts for industry (Šercer et al., 2019).

1.3. Wire harnesses and need for testing

Cable harnesses are a key component of modern electrical and electronic systems. They are responsible for the reliable transmission of both signals and energy in areas such as automotive, aviation, household appliances, and industrial automation. Problems with cable connections can lead to system failures, safety hazards, or costly downtime. Therefore, effective harness testing is an essential step in quality assurance processes (Frazier, 2014; Shahrubudin et al., 2019).

1.4. Commercial solutions and their limitations

Professional electrical harness testers are available on the market, offered by companies such as Weetech (e.g., model WK260). These devices offer precise measurements and extensive capabilities, but their price is significantly high, often reaching tens of thousands of euros. Such costs make them inaccessible to small and medium-sized companies that are looking for easier and more affordable solutions.

1.5. Justification for the implementation of the project

The presented project addresses a specific gap by offering the design and creation of a low-cost harness connection tester. The device is based on the ESP32 microcontroller, which provides multiple inputs and outputs, as well as the ability to communicate via Wi-Fi and Bluetooth while maintaining high computing performance at a low price. In addition, the tester's housing and structural components were manufactured using FDM 3D printing technology, which enabled rapid and economical prototyping (Gibson et al., 2021; Bochnia, Kozior, 2024). The combination of these two technologies has resulted in an innovative, inexpensive, and functional device for testing electrical harnesses.

2. Purpose and scope of the research

The main purpose of the research was to develop and implement a prototype device for testing electrical harness connections, combining the advantages of the budget ESP32 microcontroller with the versatility of FDM 3D printing technology. This device was designed to support the testing of harnesses used in low-voltage and low-current applications, offering both functionality and affordability.

The specific objectives included:

- Design and commission a custom printed circuit board (PCB) using KiCAD software, integrating an ESP32 microcontroller, input/output expanders, and basic security components.
- Development of modular software in C++ using the Arduino framework and the Visual Studio Code development environment.
- Designing the case and structural elements of the tester in Fusion 360 software, then manufacturing them using FDM technology on a Prusa MK3S+ 3D printer.
- Functional tests of the prototype were conducted, which included verification of up to sixty-four possible connections, corresponding to 128 measuring points.
- Conducting an economic analysis of the device and comparing its costs and functionality with other testers available on the market.

The scope of the research covered a complex engineering process, which included individual stages, from concept formulation and electronic system design, through software development and additive manufacturing of the housing, to the assembly, validation, and cost analysis of the final prototype. This comprehensive approach reflects the interdisciplinary nature of modern mechatronics, in which electronics, programming, and additive manufacturing are tightly integrated (Siemiński, Budzik, 2015; Gibson et al., 2021; Bochnia, Kozior, 2024).

3. Research/project methodology

3.1. ESP32-based control unit and functional design

The device is based on the ESP32 Devkit V1 microcontroller. It was chosen as the central control unit due to the substantial number of available GPIO lines and its serial communication capabilities. In order to enable testing of more connections than those directly available in the microcontroller itself, 16 PCF8574 expanders were used, which were connected within the I²C bus. This solution made it possible to increase the number of available input/output lines (GPIO) to 128, which corresponds to the possibility of setting up sixty-four test connections in a paired configuration.

A 2.8-inch graphic display operating in the SPI standard is used to operate the user interface. The display has been integrated with:

- an SD memory card reader for storing test configuration files;
- a touch panel for interactive operation of the device.

The CSV configuration files contain a list of test programs as well as additional data on wire harnesses. After loading the data from the SD card, the user can select the appropriate test program via the touch screen. The system then provides the user with information on the status of all analyzed connections.

ESP32 plays a key role in coordinating the operation of all system modules. It is responsible for sending signals to I²C expanders, receiving feedback from tested connections, communicating with the display via the SPI bus, and interpreting information from the memory card. This type of architecture enables modularity and facilitates project scaling, while ensuring intuitive operation thanks to the use of a touchscreen graphical interface.

3.2. Software and development environment

The tester software was designed in C++ using the Visual Studio Code environment, enhanced with the PlatformIO extension. This extension enables effective library management and code compilation. The Arduino framework was used to manage the microcontroller, which enables effective integration with hardware modules and provides broad access to ready-made libraries.

The code structure has been designed in a modular way, which ensures transparency and ease of further expansion. The following parts of the program have been distinguished:

- display and touch panel support – responsible for the user interface, displaying messages, and selecting the test program;
- connection test logic – control of signals sent by I²C expanders and interpretation of results;
- SD card support – reading configuration files in CSV format, containing a list of test programs and additional information about harnesses;
- auxiliary modules – including serial communication support, diagnostics, and error handling.

This division of the software contributes to easier maintenance and development. Changes to the test configuration can be made by editing CSV files, eliminating the need to recompile the entire software. Using a touch screen, the user can intuitively select a test program, after which the device automatically performs a verification procedure for all available connections.

3.3. PCB project

The schematic and PCB board were designed using KiCAD software, which enables the generation of comprehensive electronic documentation for the device. The project involved the integration of key system components:

- ESP32 microcontroller, acting as the central unit;
- 16 PCF8574 expanders supporting up to 128 GPIO lines via the I²C bus;
- an R-78E3.3-1.0 converter, providing a stable 3.3 V supply voltage for the circuit;
- filter capacitors, responsible for voltage stabilization;
- Zener diodes, which functioned as ESD protection for the input/output lines.

The printed circuit board (PCB) design features printed pin numbering, which facilitates the identification of individual pins during the process of connecting the tested wires. In addition, the components have been arranged appropriately to ensure optimal readability of the layout and ergonomics during the assembly process in the enclosure.

The production process for the board was outsourced to an external contractor based on the design documentation. As a result of these activities, a professionally manufactured prototype board was obtained, which is ready for integration with the other components of the device.

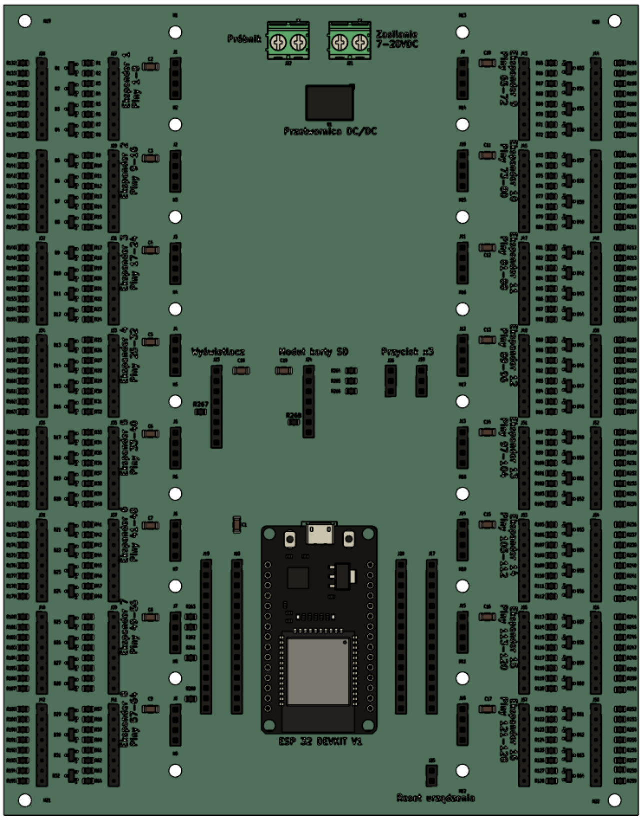

Figure 1. PCB design of the wire harness tester in KiCAD

(source: own study)

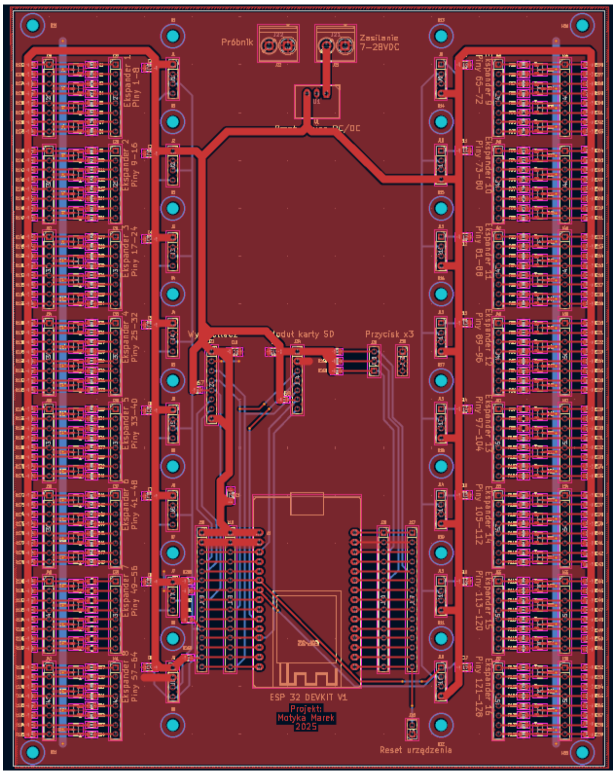

Figure 2. Visualization of PCB connections in KiCAD

(source: own study)

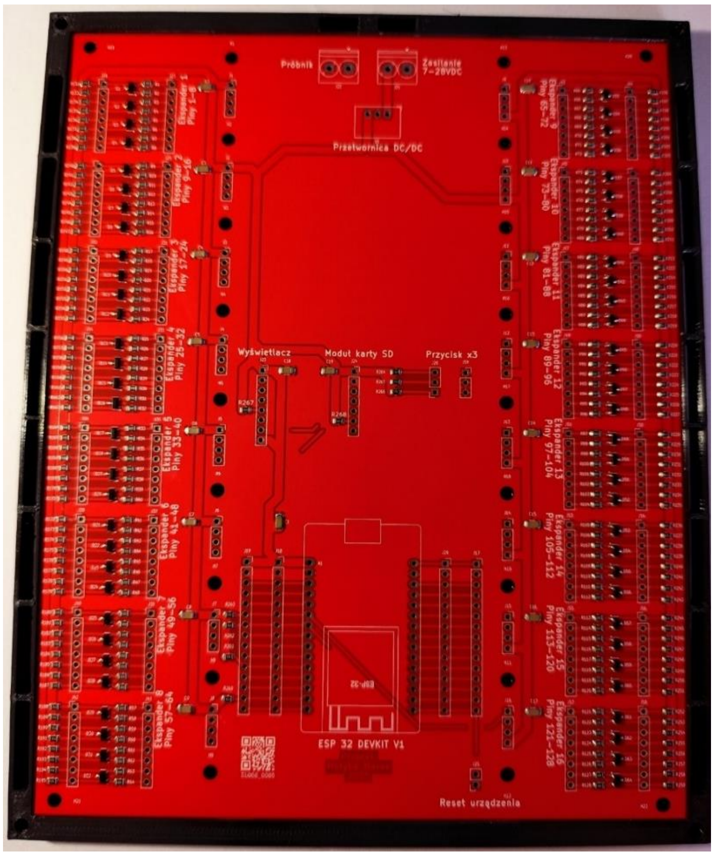

Figure 3. Assembled PCB of the wire harness tester

(source: own study)

3.4. Housing design and additive manufacturing

The tester housing and fasteners were designed in Fusion 360, which offers advanced modeling capabilities for both individual components and complex assemblies, ensuring high precision and accuracy in the design process. The basic design assumptions included:

– mechanical protection for the PCB and electronic modules;
– easy access to input and output connectors;
– easy assembly and disassembly;
– ergonomic operation and compact dimensions.

The three-dimensional models were exported to STL format and then prepared for printing using PrusaSlicer software. The production process was conducted using Fused Deposition Modeling (FDM) 3D printing technology with a Prusa MK3S+ printer.

Various printing materials were used to construct the housing and components, selected according to strength and functional requirements:

– PET-G was used as the material to produce key housing components, including the body, base, side walls, front panels, and transport handles. It was chosen for its advantageous properties, such as good mechanical strength, resistance to temperature and humidity changes, and ease of printing. Polycarbonate (PC) – used in applications involving the fastening of expanders and cable sockets. Polycarbonate has exceptionally high mechanical and impact resistance, which is a significant advantage in applications exposed to frequent connection and disconnection of cables.
– PA+15CF (carbon fiber reinforced nylon) is a material used in the production of fasteners that must meet high strength requirements, including applications such as side fasteners for structures. The addition of carbon fiber significantly increases the stiffness and mechanical strength of the components, while minimizing their tendency to deform.
– TPU was used in the construction of flexible elements, such as spacer feet and the upper housing of the USB port. Thanks to its flexibility, thermoplastic polyurethane (TPU) can absorb vibrations, provides anti-slip properties, and is highly resistant to mechanical damage caused by pressure or impact.

The use of varied materials has enabled the mechanical and functional properties of individual parts to be optimally matched to their function within the entire device. As a result, the housing combines durability, ergonomics, and aesthetic design.

4. Prototype description and results

The designed tester was implemented by mounting it on a previously developed PCB board, using expansion modules and housing components made with 3D printing technology. The central element of the device is the ESP32 Devkit V1 microcontroller, which plays a key role in coordinating the operation of all components.

The printed circuit board (PCB), designed using KiCAD software, integrates a microcontroller with sixteen PCF8574 expanders. This configuration increases the number of supported GPIO lines to 128, allowing testing on sixty-four connections. The R-78E3. 3-1. 0 converter provides a stable power supply to the circuit, while filter capacitors and Zener diodes play a key role in protecting components from interference and electrostatic surges.

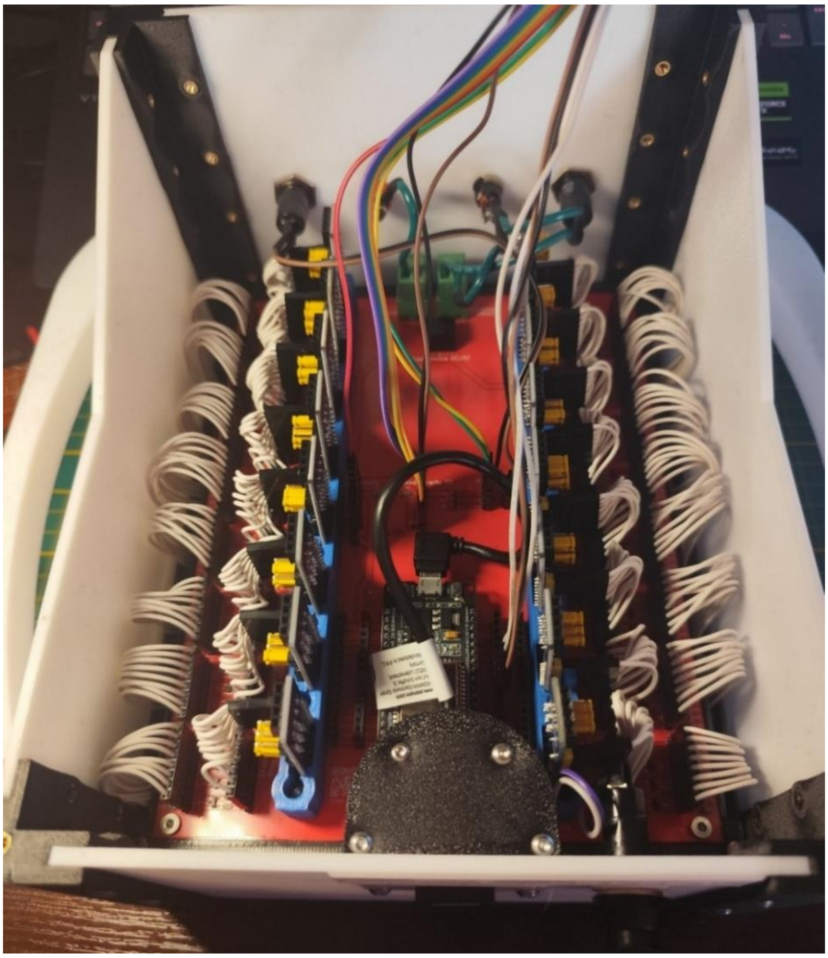

Figure 4. Internal view of the tester showing the PCB and wiring

(source: own study)

A 2.8-inch touchscreen display equipped with an SD card reader is used for user interaction. This solution enables efficient loading of test configuration files saved in CSV format, with the process being controlled via an interactive touch panel.

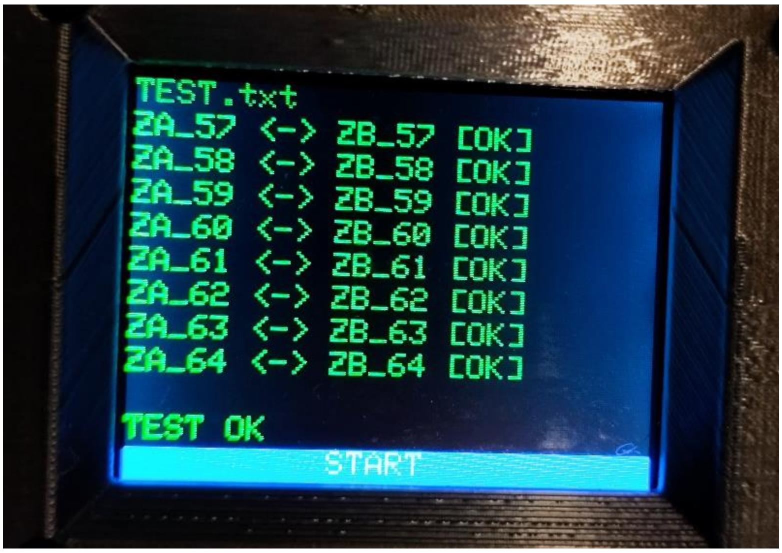

Figure 5. User interface of the 2.8-inch touch display during operation

(source: own study)

All electronic components were placed in a housing designed using Fusion 360 software and manufactured using Fused Deposition Modelling (FDM) 3D printing technology. The housing is made of components of different materials, including: PET-G, which forms the main structure and panels; polycarbonate (PC), used to manufacture expander mounts and sockets; PA+CF composite, characterized by high rigidity in structural applications; and TPU, used in the production of spacer feet and flexible covers. The material diversity used in the analysed context made it possible to achieve an optimal combination of features such as durability, functionality, and ergonomic use.

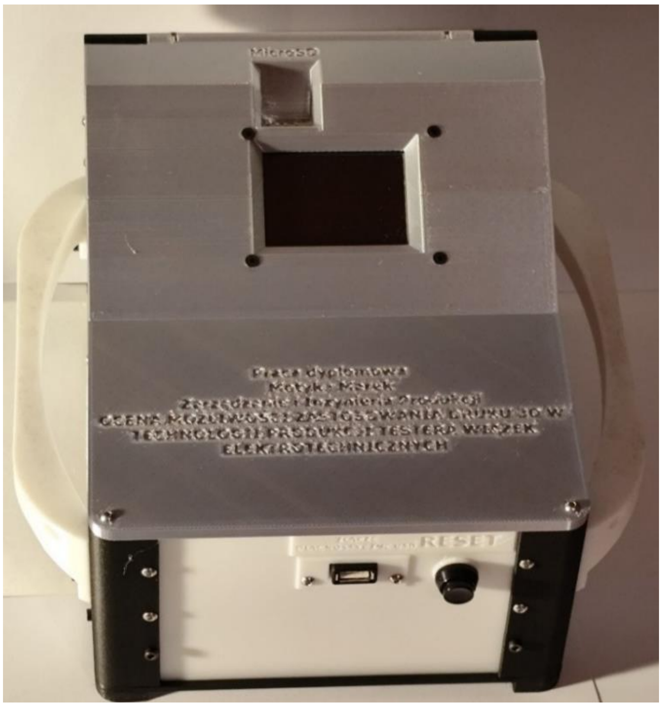

Figure 6. View of the assembled prototype of the wire harness tester

(source: own study)

The developed prototype device is distinguished by its compact design, intuitive user interface, and simplified process of connecting the tested cables. The design has been developed in such a way as to enable effective expansion of its functionality through the introduction of new test programs and modifications to the housing.

5. Economic analysis

The developed prototype of an electrical wiring connection tester was subjected to a cost analysis to assess the cost-effectiveness of its design in comparison with existing commercial solutions on the market.

The cost estimate included both electronic components and materials used in the 3D printing process. The total cost of purchasing electronic components, including the ESP32 microcontroller, PCF8574 expanders, R-78E3 converter. 3-1. 0, touch display, SD card module, and passive components such as resistors, capacitors, and diodes, amounted to several hundred zlotys. Additionally, the costs of filaments used in FDM technology (PET-G, PC, PA+CF, TPU) were considered, which in the case of the prototype were relatively low due to the limited amount of material used. The total cost of manufacturing the device was approximately PLN 770.

For comparison purposes, professional beam testers, represented by Weetech devices, are significantly more expensive. The WK260 model costs around PLN 38,000. The difference in cost is therefore significant; constructing our own prototype device has enabled us to obtain a fully functional tester at minimal expense compared to commercially available solutions.

However, it should be noted that the developed prototype does not provide such advanced functionality or the same precision as professional-grade devices. The aim of the project was to develop an economical and flexible tool for testing low-voltage and low-current harnesses that could be implemented in small and medium-sized enterprises. From a cost analysis perspective, the project showed that the integration of the ESP32 microcontroller with Fused Deposition Modelling (FDM) 3D printing technology enables the development of an innovative and economical solution that is an alternative to expensive industrial testers.

6. Opportunities for further development

The developed prototype of an electrical harness connection tester provides a foundation for further development of the technology in various directions, enabling the device to be adapted to more advanced applications. Potential areas of development may include:

- increasing the number of supported connections – by using additional I²C expanders or other microcontroller architectures;
- extending the range of functionality – adding wire resistance measurement, continuity tests with current control, and even simple insulation measurements;
- improving the user interface – developing software with more extensive menus, test reports saved in files, and wireless communication capabilities (Wi-Fi, Bluetooth);
- use of other 3D printing technologies – e.g., SLA technology for components requiring greater precision or SLS for parts with high mechanical resistance;
- integration with production systems – the ability to send test results directly to production management systems (MES/ERP), which would increase the usefulness of the device in industrial conditions.

As a result of the modifications indicated, the tester under development has the potential to evolve in the future not only into a prototyping tool, but also into a fully functional device supporting quality control processes in the electrical engineering industry.

7. Conclusions

The completed project enabled the design and construction of a prototype electrical wiring connection tester based on the ESP32 microcontroller and Fused Deposition Modeling (FDM) 3D printing technology. The device achieved its objectives, enabling effective testing of up to sixty-four wire connections in the context of low-voltage and low-current applications.

The use of the ESP32 microcontroller in combination with PCF8574 expanders has significantly increased the number of supported inputs and outputs, which has contributed to the flexibility of the device and facilitated its further development. The software, developed in C++ using the Arduino framework, enabled the creation of an intuitive user interface that is operated via a 2.8-inch touch screen and configuration files in CSV format.

The use of 3D printing technology enabled the efficient and economical production of the housing and structural components. The selection of materials such as PET-G, PC, PA+CF, and TPU made it possible to obtain diverse mechanical properties that are appropriately matched to the specific functions of individual components. This applies in particular to parameters such as strength, stiffness, flexibility, and vibration resistance.

An economic analysis showed that the total cost of the prototype was approximately PLN 770, which is a fraction of the cost of professional testers available on the market (PLN 38,000). The device can therefore be an attractive alternative for small and medium--sized enterprises that need inexpensive and functional tools for testing harnesses.

In summary, the project has demonstrated that combining microcontroller technology with additive manufacturing enables the development of innovative and low-cost engineering solutions that can be further developed and adapted to industrial needs.

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