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The Idea of RFIDtex Transponders Utilization in Household Appliances on the Example of a Washing Machine Demonstrator

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Abstract: Modern textronic RFID transponders offer a lot of new possibilities for household appliances designers. Possibility to implement new functions is most evident in clothes washing and ironing techniques, where the information stored in the memory of the RFID transponder sewn into the textiles can be used to choose the most appropriate ironing program for a given type of fabric or to select the best washing program for different clothes placed in a drum of washing machine. The purpose of the work was to propose, design, and develop a laboratory stand to demonstrate usage of RFIDtex transponders in a washing machine. The developed device enabled simulation of the presence of textiles equipped with RFIDtex transponders in a washing machine drum. A set of measurements of the constructed device readout efficiency of textronic transponders placed in the drum was also performed. The device firmware, which manages multiple data readings from tags inside the drum for the performed by integrated RWD (read/write device), was also prepared and implemented. This allowed the efficiency of the identification of textiles equipped with RFIDtex transponders to be increased. RFIDtex transponders can also be used in the future to provide precise information about textiles to the washing machine. Based on this information, device will be able to reduce power consumption.

Keywords: RFID; textronics; home appliance; washing machine

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1. Introduction

It is human nature to look for ways to make everyday life easier. One of the activities people have been looking to automate is washing clothes. The first washing machine working with usage of a rotating drum was patented in 1858 by H. Smith. In 1874, a washing machine designed by W. Blackstone came into use in households. Originally, the device was built as a gift for a wife [1].

The development of an electric drive at the edge of the 20th century enabled the construction of washing machines with a drum moved by an electric drive [2–4]. However, the principle of washing, which includes the process of movement of clothes in water with detergent for a certain period of time, has not changed [5–7]. The design of the washing machine has only been modernized and modified [8–13]. Microcontrollers have been added to washing machines, allowing controlled dosing of detergents, water, regulation of water temperature, and drum rotation speed [14]. It does not change the fact that it is the user who still has to decide which clothes should be placed in the drum for a single wash cycle and determine the washing temperature and the drum rotation speed. The user must also choose the detergent that is most appropriate for the bundle of textiles in the drum and the appropriate amount of it. Incorrect settings selection can damage textiles in the washing machine drum.

The solution to these problems seems to be the use of systems in washing technology devices that allow precise information about the fabrics loaded into the drum to be obtained, and on this basis, determine all the settings of the washing program by the algorithm of the microcontroller built into the device. To make this possible, it is necessary to equip clothes with information carriers in the memory in which the precise parameters of washing the fabric can be saved at the stage of its production. One of the potential carriers of this type of information may be the RFIDtex textronic transponder developed as part of the research carried out at the Rzeszów University of Technology [15]. The use of such transponders creates completely new possibilities in the scope of the fabric washing process.

The use of RFID systems in household appliances can create a completely new approach to automatic washing. Human involvement in selecting a washing program can be kept to a minimum. Characteristics of water temperature in individual stages of washing as well as the type, amount, and time of detergent dosing in addition to the rotation of the drum during washing are determined fully automatically on the basis of information read from RFID transponders placed in fabrics. Additionally, connecting this type of device to the Internet makes it possible to update washing programs to adapt them to new types of fabrics. This approach can extend the life of the device and optimize the use of electricity, water, and detergents, making the washing machine more environmentally friendly.

Unfortunately, the washing machines that use RFID systems are not available on the consumer market. Only existing studies are those on the impact of the washing process on RFID textile transponders in standard washing machines [16–21]. As a result, it is not possible to test the operation of the experimental RFIDtex transponders under conditions similar to those of the real ones. Hence, there is a need to build a model of an automatic washing machine that allows laboratory tests and tests of the effectiveness of reading data from textronic transponders integrated with fabrics. Only in the case of ensuring high efficiency of identification and carrying out a comprehensive reading of information from the memory of transponders embedded in fabrics, it is possible to implement the above-mentioned functionalities in the future.

The developed model enabled simulation of the first phase of washing fabrics, which means placing fabrics with sewn transponders in the drum and controlling the drum in such a way that it is possible to read information about textiles inside it. In addition, the model control program should suggest the best washing program for the fabrics placed in the drum. This study describes the mechanical, electrical, and electronic structure of the laboratory model as well as preliminary tests of the effectiveness of identifying fabrics with integrated RFIDtex transponders. Procedures related to transponder reading algorithms, the communication protocol model, and the selection of an appropriate washing program remain the subject of a separate study.

2. Principles of the RFID System

Usually, a radio frequency identification (RFID) system consists of an RWD (read/write device) equipped with at least one antenna and at least one transponder that includes antenna circuit, microprocessor, and memory in its structure (Figure 1). The serial number of the transponder and the data about the identified object are usually stored in its integrated memory. The read/write device reads data from the memory of the RFID transponder. The read data are most often forwarded to the host hardware and software. The second most important function of the read/write device may also be to write data to the memory of the transponder, if necessary.

This allows for updating the contents of the transponder's memory at various stages of the identified object's life cycle. The process of data exchange with a transponder takes place only within the interrogation zone (IZ) of the RFID system [22–24]. If there is only one object with an RFID transponder in the IZ, the process of object recognition is called single identification. If many objects equipped with transponders are located in the IZ, data exchange with all of them takes place using the anticollision mechanism according to the algorithm defined by the protocol, and it is called multiple identification [25,26]. An

RFID system in which the location of the RWD antenna with respect to the transponder is constant and the communication time is not limited is called a static system. Therefore, the definition of IZ can be understood as a group of field, electrical, and communication conditions that must be met to gain a certain recognition of a multiple objects tagged with transponders.

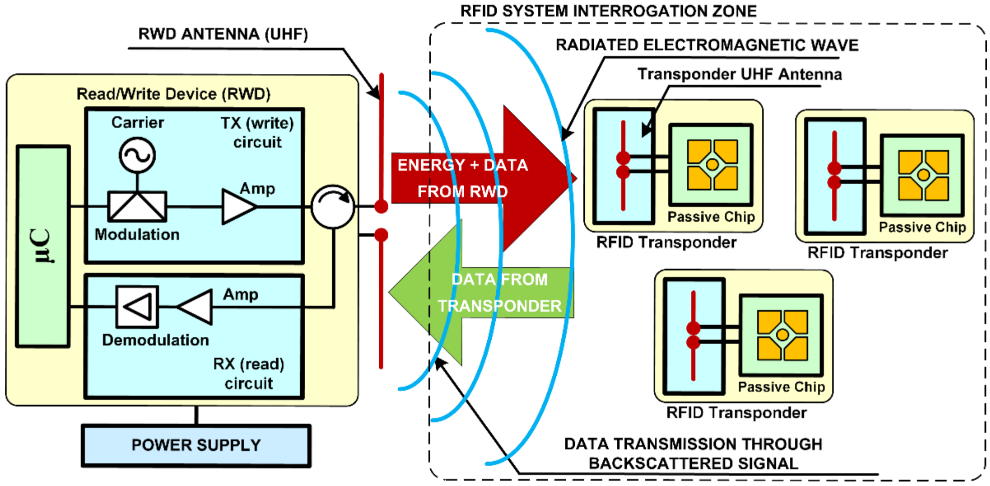

Figure 1. Simplified block diagram of the multiple RFID system.

In recent research works, the synthesis of IZ comprised experimental studies and analytical and numerical calculations of the range of the RFID system [22], but in real implementations, the method of trial and error is often used [27]. In the case in which many objects are present inside the IZ and their position and orientation can change dynamically, the calculation of the parameters of the RFID system is even more demanding due to the parameters describing the dynamics of changes in the system. To systematize the operation of RFID systems, several standards have been developed. The most popular examples are ISO15693 [28], ISO14443 [29], and ISO18000 [30].

3. Types of RFID Transponders

The UHF frequency range was selected because of the possibility of using transponders compatible with the ISO18000-63 standard. The advantage of using this type of transponders is the possibility of identifying many objects at the same time, thanks to the anti-collision protocols provided in the standard.

UHF RFID radio identification systems typically operate in the range of 860 to 960 MHz and also at a selected frequencies of 2.45 and 5 GHz. Choosing the correct value of working frequency depends on the region of the world. On the European continent, RFID systems operate in the 865–870 MHz range according to the protocol specified by ISO/IEC 18000-63 [31]. There are currently four types of transponders that function in this frequency range: passive, semi-passive, semi-passive with energy harvesting system, and textronic.

The most common RFID passive transponder contains an antenna and a chip (Figure 2a). Its cases may take various shapes (key rings, cards, labels, glass tubes, discs, or coins) and be made of many materials (ceramic, plastic, metal, glass, etc.). Access to the internal memory of the transponders is possible only through the RWD with the use of radio interface [32].

Another group of growing importance on the market is semi-passive RFID transponders with an integrated additional power supply (e.g., a removable or non-removable lithium battery) (Figure 2c). In general, extra battery power is used to increase readout range and thus the interrogation zone [32] but it can also be used to provide additional functions implemented in the transponder structure (Figure 2b). Additional transponder functions may take various forms such as measurements of physical quantities [33] (e.g., temperature, pressure, and humidity), storage of collected information in extended memory, or exchange of data via additional radio or cable interfaces [34–36].

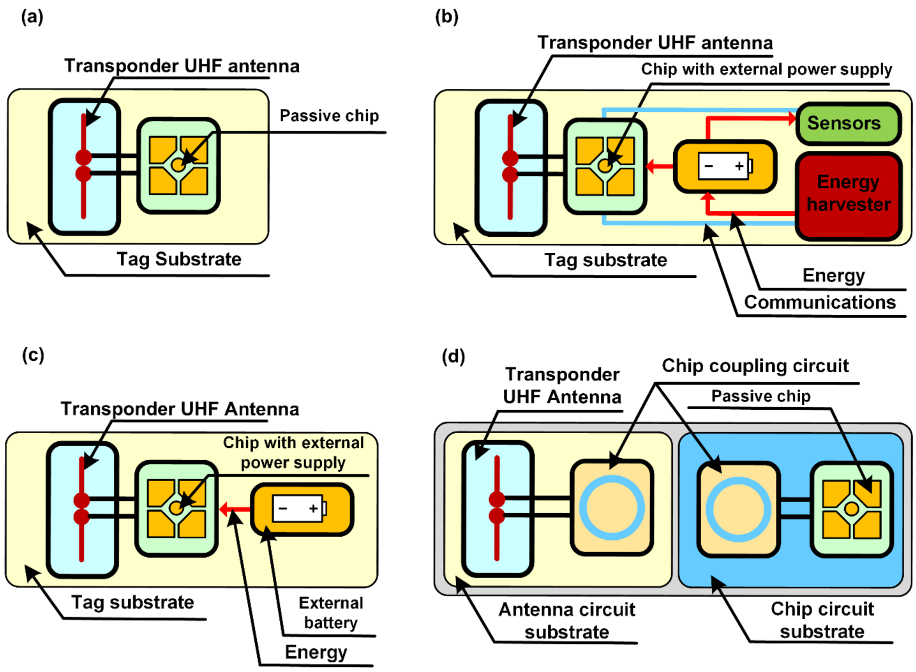

Figure 2. Simplified block diagrams of different types of RFID UHF transponder: (**a**) passive transponder; (**b**) semi-passive transponder equipped with an energy harvesting system and an autonomous set of sensors; (**c**) simple semi-passive transponder equipped with battery; and (**d**) RFIDtex textronic transponder with separated chip and antenna.

Regardless of the frequency band, in classical terms, an RFID transponder is a combination of a chip and an antenna [32]. Most often, such a device is built as a uniform structure in which the chip is soldered [37], glued [38], or otherwise [39] connected to the antenna. In this structure, the transponder antenna is made of conductive materials on a rigid substrate (low-iron laminate [40], ceramic [41], etc.) or flexible [42] (paper [43], PET [44], Kapton [45], etc.). According to the modern concept of automatic RFID identification systems, transponders are attached to objects in various ways, either permanently or temporarily [32]. This causes transponders to be produced in various shapes. There is no universal transponder design to mark any object. In each case of RFID system development, the transponder should be selected from ready-made constructions or (which is more advantageous) a solution dedicated to a given object should be designed while taking into account many physical, chemical, electromagnetic field, electrical, and communication conditions of its operation in the target RFID system application [46–51].

The latest approach to the design of RFID transponders is shown in Figure 2d. In this type of construction, the chip and the antenna are placed on physically separated and galvanically isolated bases. The antenna may be embroidered or sewn with conductive threads as well as other techniques, e.g., by pressing a conductive wire that constitutes the antenna into the fabric. The chip-containing module may be manufactured as a blank (e.g., button or label) and integrated into the fabric by sewing it into a marked textile item. The microelectronic module may consist of a typical printed circuit board (PCB or other rigid substrate) to which an RFID chip is attached. The resulting semi-finished product can then be attached to the fabric using techniques used in the textile industry. With this concept (Figure 2d), the problems of connecting the RFID chip to a flexible and jagged textile substrate can be avoided and thus the semiconductor integrated circuit (IC) can be protected [52–55].

4. Internet of Textile Things

The application of RFID systems using RFIDtex transponders integrated with fabrics in household appliances and especially in laundry technology [56–59] is perfect for sup porting the Internet of Textile Things (IoTT) ecosystem [60,61]. As textronic transponders are intended to be used throughout the lifecycle of a marked textile product, their complete implementation opens completely new possibilities [62–64] in terms of production and sale as well as subsequent use and recycling of textiles. The use of RFID systems in laundry technology expands the possibilities of effective management of the life cycle of the IoTT product [65,66]. Because RFIDtex transponders are permanently integrated with the product already in the production and quality control stage, their memory can contain detailed data on the parameters of the fabric from which the product is made as well as the performance parameters of the product. In the next steps of the cycle, the data can be supplemented in warehouse inventory systems and can be used for logistic and advertising tasks in the stage of wholesale and retail distribution. Then, as part of the after-sales service, washing machines equipped with RFID identification systems can use the collected information to select the best washing programs for the set of clothes loaded by the user into the drum, the selection of detergents used in the process of washing fabrics, or the amount of water used by the devices (Figure 3). This approach may influence the optimization of energy consumption of the currently mass-used automatic washing machines. At the last stage, the data collected throughout the product life cycle can be used for the safe treatment of waste.

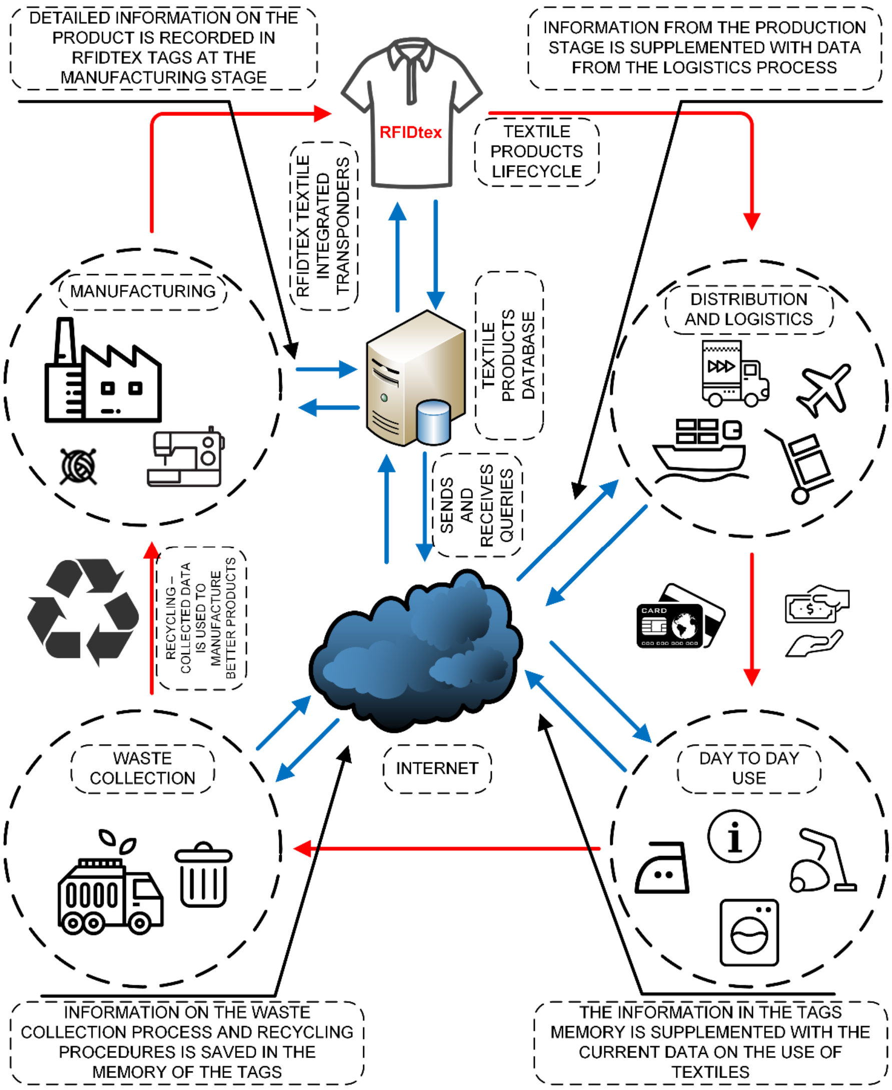

Figure 3. Simplified diagram of the RFIDtex equipped textile lifecycle and possibilities of RFID enabled home appliances in Internet of Textile Things (IoTT) applications.

5. Idea of the RFIDtex-Enabled Washing Machine Model

The main aim of the developed laboratory model of a washing machine was the demonstration character of the use of RFIDtex textronic ISO18000-63 transponders in future modern household appliances and the possibility of conducting identification efficiency measurements in an environment that simulates a washing machine drum. The main task of the constructed device was to read the information from the integrated memory of the transponders sewn into clothing placed in the machine drum. Based on the data readouts from multiple transponders, the system was also designed to assist in making decisions about the appropriate washing program and to display information on the selected program. Additionally, the system was equipped with a transponder programming function using a read/write device and a quick single transponder readout option. These functions are used by the user to independently save additional information in the memory of transponders embedded in clothing.

Figure 4a shows a simplified block diagram of the designed and constructed device. The central element was the STM32 microcontroller which was responsible for receiving, transmitting, and processing data. The microcontroller controlled the operation of the read/write device, display, and the driving unit of the washing machine drum. A touch LCD display was directly connected to the microcontroller. Due to this, the entire device could be managed and the processed data was presented in a user-friendly form. The UHF FEIG read/write device was connected to the microcontroller using the RS232-UART converter. To be able to read the data from the transponders sewn into the clothes placed in the drum of the washing machine model, three external antennas were connected to the read/write device through the multiplexer. The microcontroller controlled the operation of the drive system. The device was also equipped with a set of sensors measuring the rotational speed of the drum to ensure speed stability and a sensor open door sensors to prevent unplanned start-up of the device.

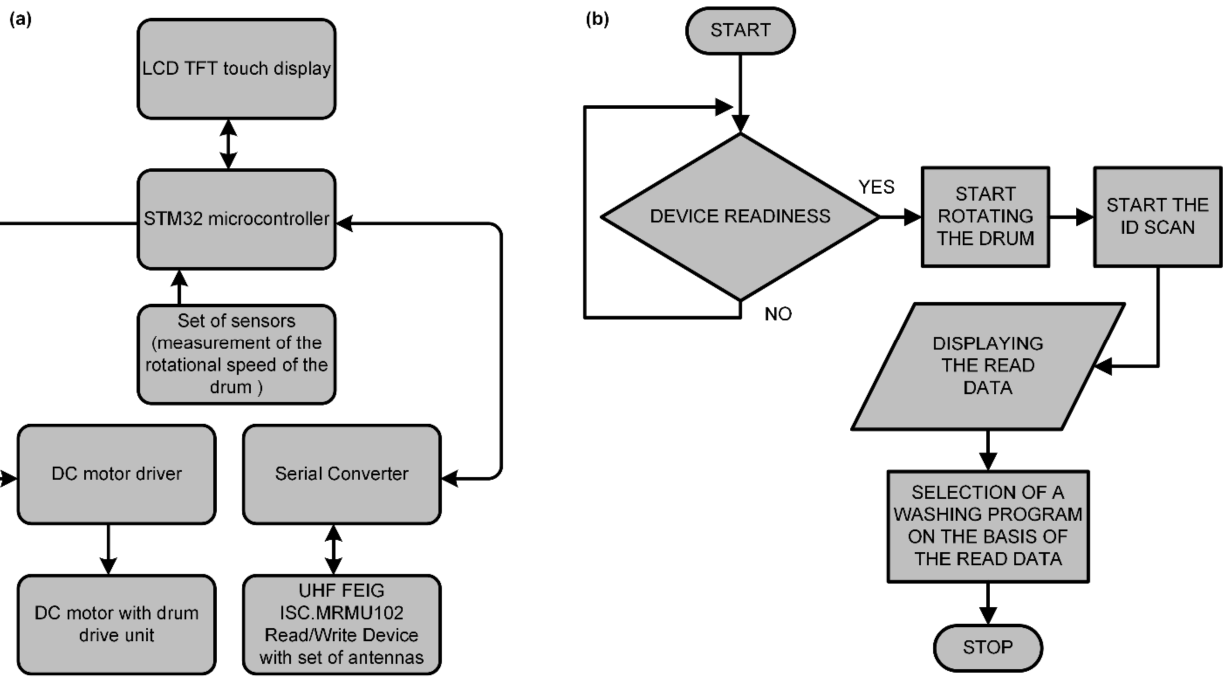

Figure 4. Simplified block diagrams of the IoTT enabled washing machine demonstrator: (**a**) electrical part; (**b**) control algorithm.

To ensure high identification efficiency in the proposed system (detailed description presented in Chapter 8), it is necessary to optimize the garment scanning process. The accuracy of the data readout from the transponder memory is influenced by many factors including the distance of the transponder from the antenna, external interference, and the number of transponders in the interrogation zone. The concept of the scanning process presented in the simplified block diagram (Figure 4b) assumes the reading of data from the transponder's memory during the rotation of the drum, and a separate study will be devoted to the details of the algorithm and the communication model.

6. Electrical Design of the Laboratory Demonstrator

The STM32 Nucleo64 microcontroller controlled the developed laboratory demonstrator. The microcontroller was equipped with a 32-bit ARM Cortex M4 processor that works with 512 KB of flash memory and 128 KB of RAM memory. The system was equipped with a built-in programmer [67].

Individual components were connected to the microcontroller according to a detailed block diagram on which the directions of information transmission are marked with arrows (Figure 5). To properly organize the spatial arrangement of the subassemblies in the device, PCB1 and PCB2 boards (Figure 6) were designed, allowing for the appropriate organization of cabling in the washing machine model housing.

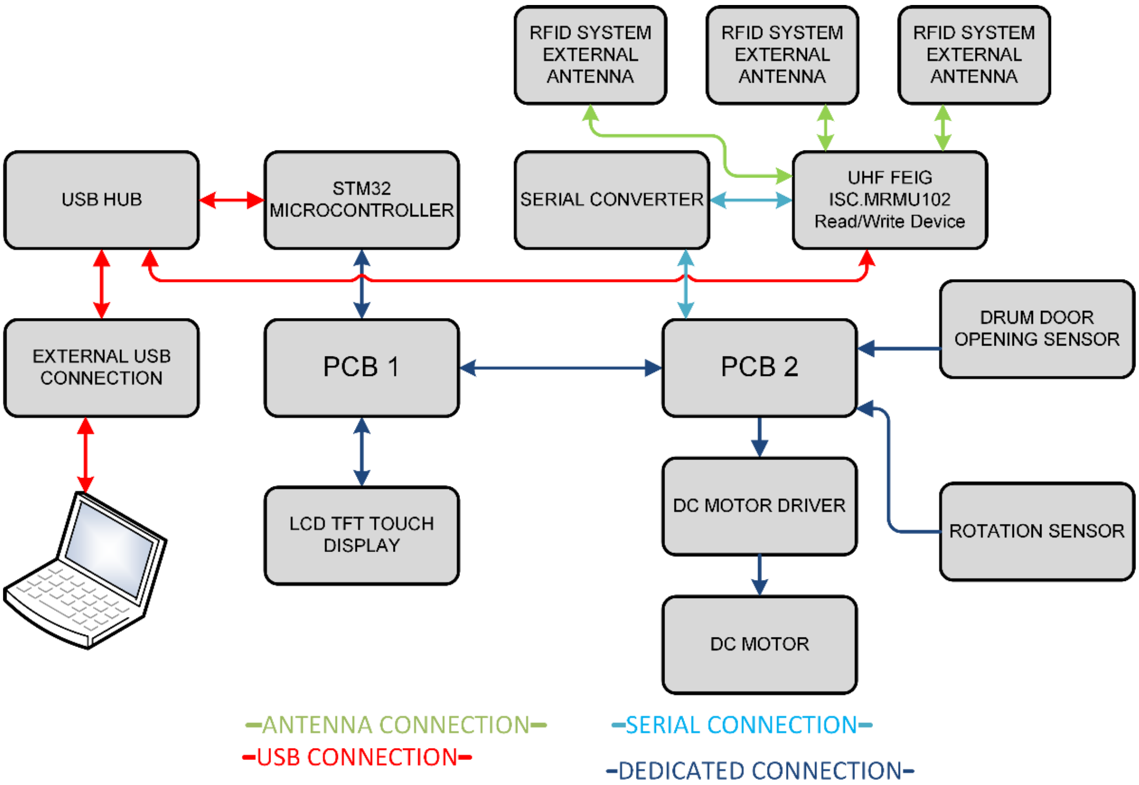

Figure 5. Detailed block diagram of the electrical part developed with the IoTT-enabled washing machine demonstrator and connected sensors.

The connection plates were also designed in such a way that multiple components could be easily mounted to the housing of the device. A microcontroller board and a display board were attached to the PCB1 board. The user could issue commands through the display with a touch screen. The display was used the control of the device and also presents information that is relevant to the user, rather than to the device.

Information about detected transponders or reports of errors that occurred while scanning the contents of the drum was presented on the LCD display. The PCB1 board was connected to the PCB2 board with an ATX connector. On the PCB2 board, a DC converter was installed. The PCB2 board was connected to external sensors, motor controller, and the FEIG RFID read/write device (by RS232 converter) through the installed set of connectors (Figure 7).

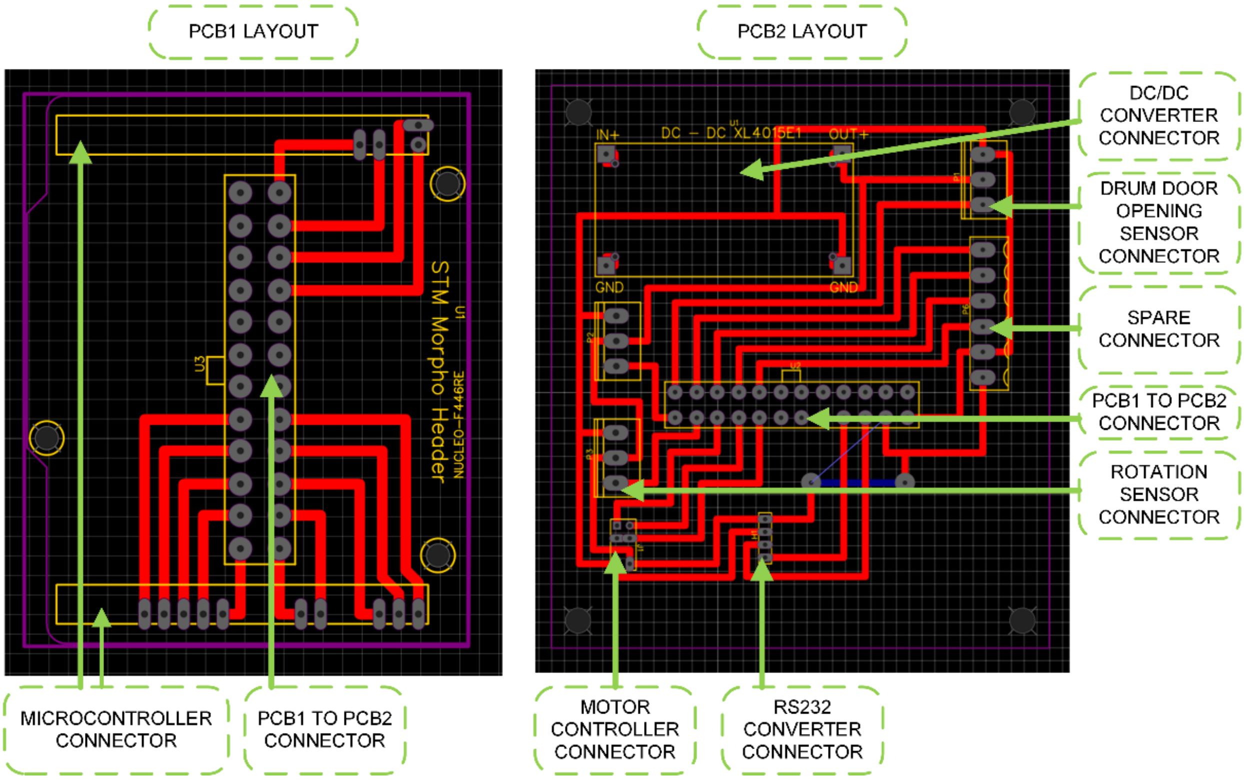

Figure 6. PCB1 and PCB2 layouts.

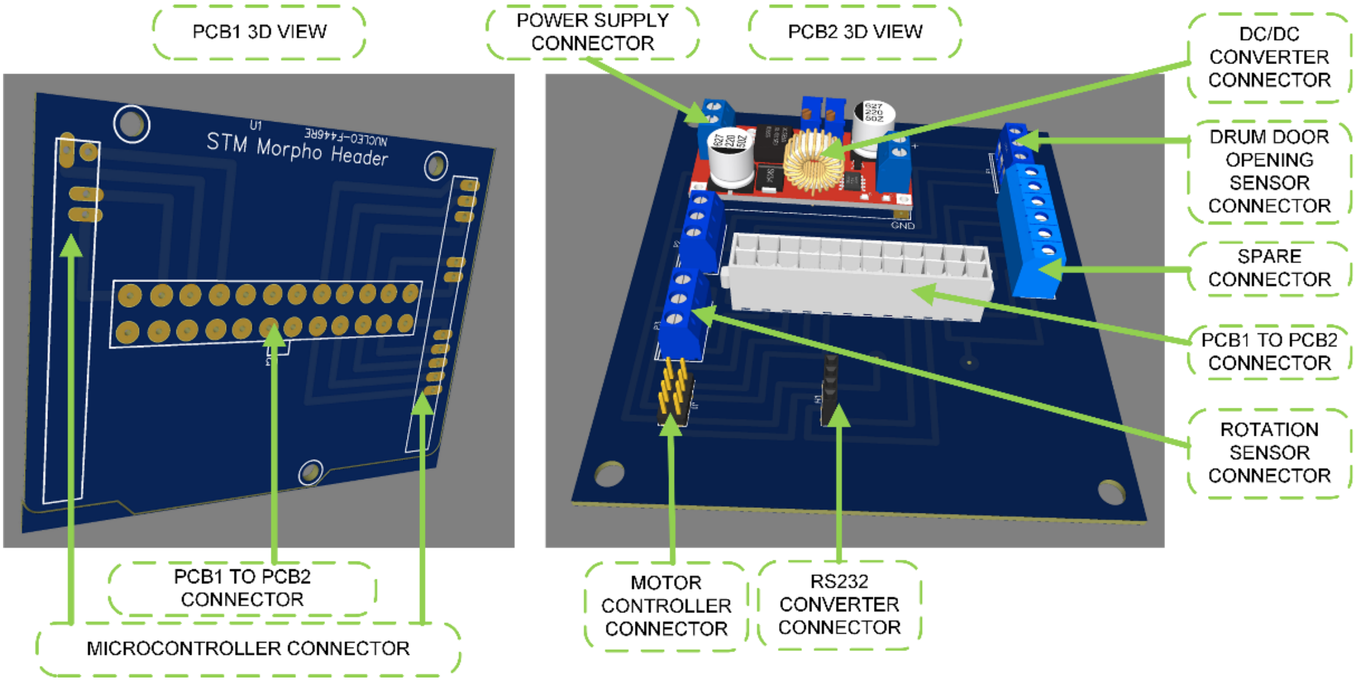

Figure 7. Three-dimensional visualizations of PCB1 and PCB2 boards.

Communication took place using a communication bus that was appropriate for each component. To communicate with the FEIG read/write device, it was necessary to use an additional converter of the RS232 signal to the UART signal. To control motor operation, the microcontroller used a DC motor driver that converted the signal from the microcontroller into the PWM signal sent to the motor, which allowed one to change the direction of motor rotation and smooth speed control and which was additionally supported by the reading from the attached magnetic sensor. A sensor of this type was also mounted on the front wall of the device to signal the opening and closing of the door. Individual electronic components were powered by a 12 V built-in DC power supply. The microcontroller, display, and sensors required a 5 V power supply. The voltage conversion was done with the XL4005E1 0.8 V–30 V 5 A step-down converter with voltage regulation and a current limiter permanently installed on the PCB2 board.

The FEIG ID ISC.MRU102 RWD [68] was used as the device responsible for reading and writing the memory of the transponders. It is a device that operates in the UHF band. Working in this frequency range gives the possibility of reading in the medium and short ranges, cooperating simultaneously with many transponders located in the read/write device interrogation zone. The RWD system was equipped by the manufacturer with communication ports such as RS232 and USB. There was also a built-in antenna on the RWD PCB. It has been adapted to work with both short- and long-range transponders. The RWD was also equipped with three connectors, allowing three additional external antennas to be added. The multiplexer integrated with the RWD was responsible for the operation of these antennas. For the developed device to function properly and effectively, ensuring adequate identification efficiency, dedicated software was developed. Its simplified structure with schematic representation is described in Appendix A.

7. Mechanical Design

The design of the washing machine model (Figure 8) equipped with the RFID identification system was made of aluminum v-slot linear rails with a cross section of 20 mm $\times$ 20 mm in the form of a rack supporting the drum (which dimensions are comparable to those of a commercial washing machine drum) with the motor and electronic systems necessary for the operation of the model. They were used to make connections between the corner connectors of the profiles fastened with M4 screws with profiles appropriate for the dimensions of the hammer nuts. The use of this type of profiles significantly facilitates the construction of prototype and demonstration devices. The structure prepared in this way allows for trouble-free structural changes that are necessary in the case of subsequent expansion or repair of the constructed device. The use of materials made of aluminum also has a reduction effect on the mass of the constructed device, which, after assembly, enables trouble-free transport. The drum mount was made of a block of aluminum that has been subjected to turning and milling. Two bearings separated by a sleeve were placed in the machined block spacer made of steel (Figure 9a). The bearing block was attached to a frame made of aluminum profiles. To prevent the bearings from slipping, two rings attached from the outside to the block were cut from the sockets. Inside the bearings, there was a two-part axle (Figure 9a) to which the drum is attached. The axis of the drum was locked by a gear wheel mounted at its end. Two rings made of an appropriately cut polycarbonate plate were used to build the drum. The front ring had a chute. The rear drum ring had a centering hole. To connect the front and rear rings, three plastic beams were made (Figure 9a). The material used for the outer layer was a 0.5 mm thick PETG plate, which ensured that the material is flexible enough to fit the shape of the structure and to model the cylindrical shape of the drum. The top layer closing the drum was applied to the structure with the use of glue.

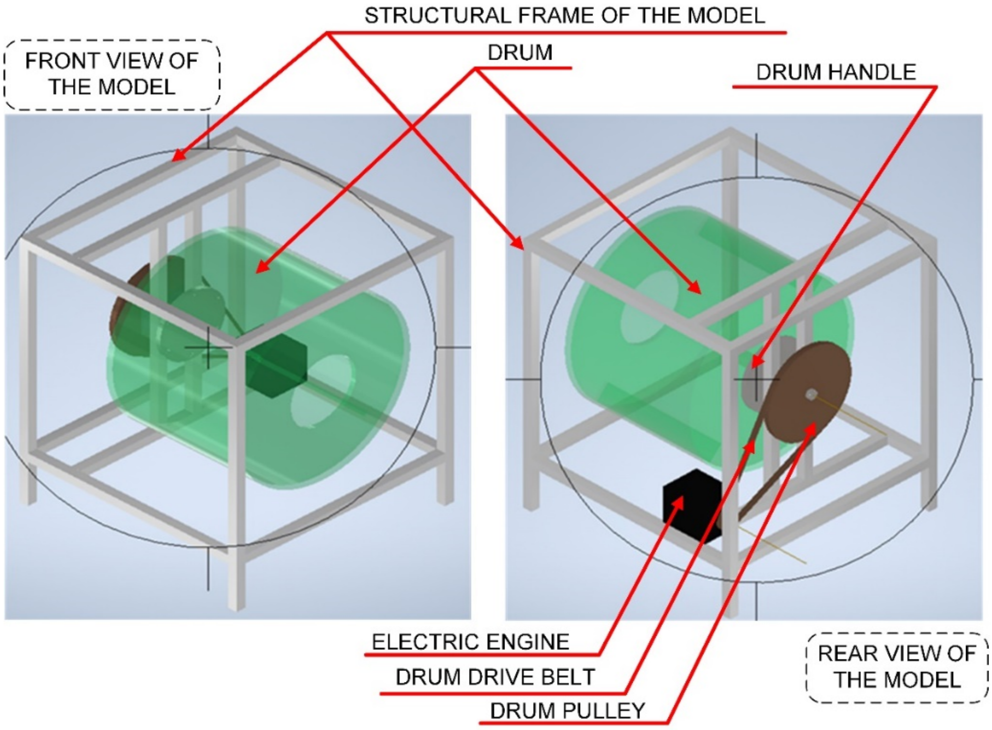

Figure 8. Developed device housing model.

To relieve the rear wall of the drum of the stresses resulting from the one-sided fastening, additional support points were installed. Two double rollers (Figure 9d) were installed under the drum so that when the drum is heavily loaded, it can lean on them without damaging them. A gear-driven motor was used to drive the drum which was used to obtain a higher torque, facilitating the movement of the drum at low speed. An additional gearbox based on two pulleys and a toothed belt was used to transfer the drive between the engine and the drum (Figure 9c). Additionally, to secure the belt and prevent its spontaneous fall, securing rings were attached to the gears (Figure 9b). The use of appropriate gear ratios aimed to level the forces that act on the engine at the moment the drum starts rotating. To ensure smooth adjustment of the motor's rotation and change of the direction of its operation by means of an appropriate program, it was connected to a microcontroller with an appropriate DC motor driver (Figure 10b). Transparent polycarbonate plates were attached to the device's structural frame from the outside. The use of transparent material enabled the observation of internal processes while protecting the internal components of the device against damage. There were openings in the side walls to facilitate the transport of the model. There was a hole in the front wall for the display and a slot to place fabrics with RFIDtex transponders inside the device. A door was attached to the front wall to prevent the badges from falling out of the drum. The door was made of five elements cut and glued together to form a structure with convex inside (Figure 10c).

Electronic components were mounted using previously made mounting holes for individual elements. On the rear panel (Figure 10b), there was a power socket, DC 12 V power supply, PCB2 board, motor controller, USB HUB, and external USB socket.

The RFID read/write device was mounted under the surface of the upper wall of the device (Figure 10a), allowing the use of its integrated antenna to program tags sewn into the fabrics. A PCB1 with an attached display and a microcontroller was attached to the front panel. The mount was made of a plexiglass plate of appropriate dimensions and the whole unit was screwed into the structure with bolts and hammer nuts. Three antennas were mounted under the drum. The antennas were positioned in such a way that their range covered the largest possible volume of the drum (Figure 10d). The antenna mounts were made of PVC foam. As the developed device was essentially a testing platform for experimental RFIDtex transponders, this effort was made to minimize the couplings that could occur between antennas and metal.

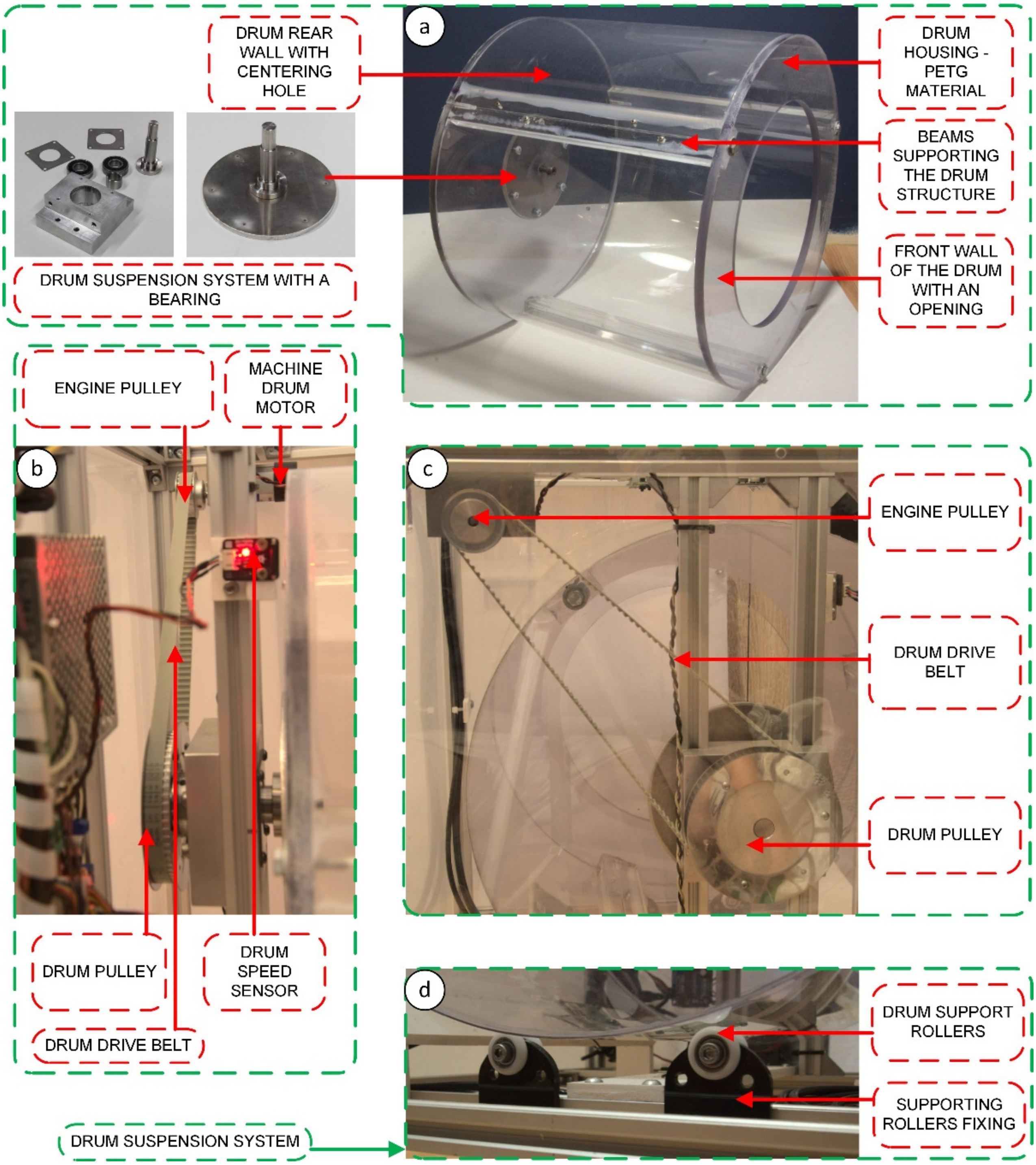

Figure 9. Mechanical design of the developed IoTT-enabled washing machine demonstrator: (**a**) drum and its suspension view; (**b**) side view of the device; (**c**) rear view of the developed device; and (**d**) drum suspension system.

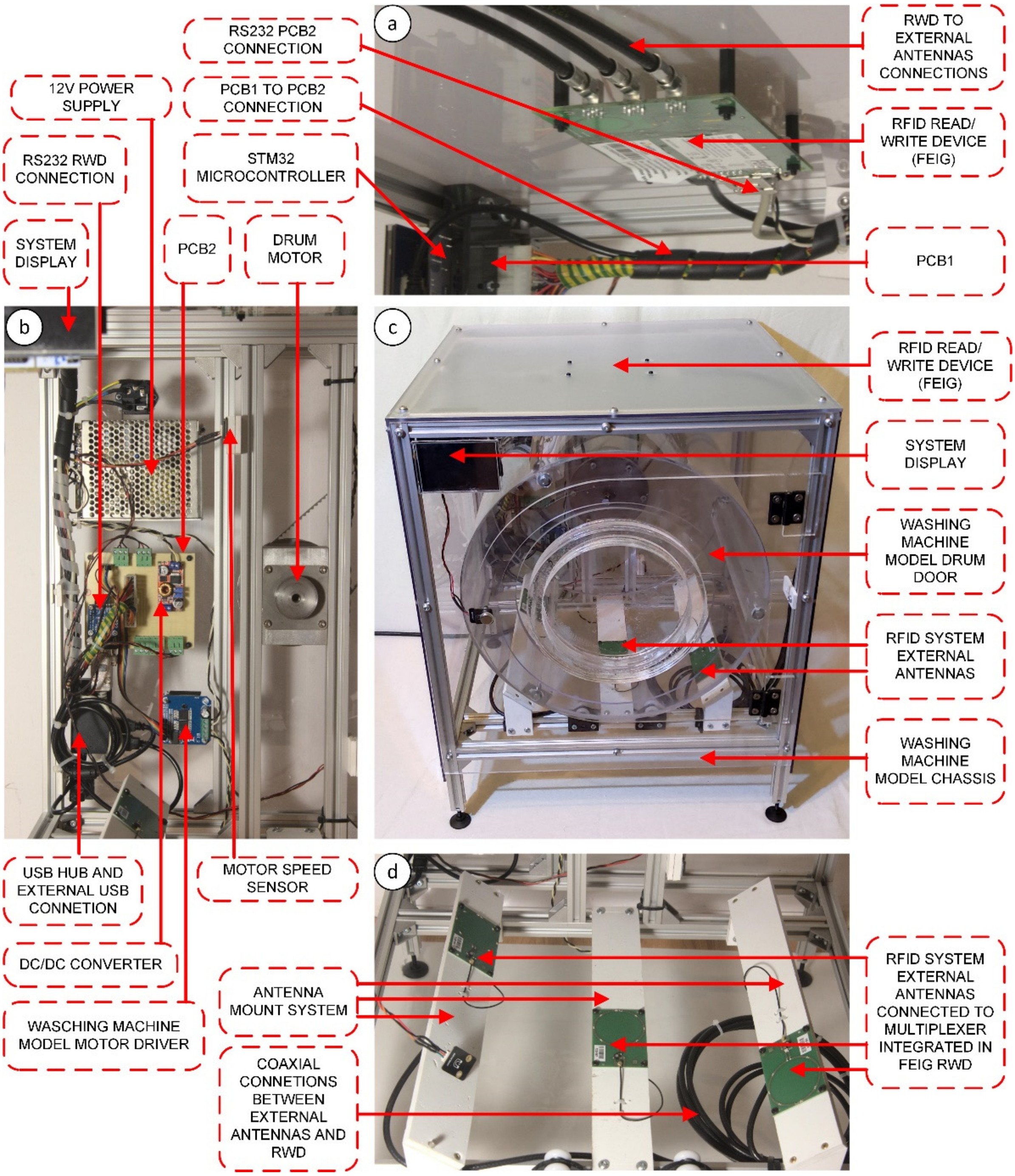

Figure 10. Assembly of electrical and electronic components in the developed model: (**a**) RWD attached to the top cover of the device; (**b**) attachment of the power supply and supporting devices to the rear part of the device housing; (**c**) front view of the device; and (**d**) attachment of the RFID system antennas to the device housing.

8. Initial Tests of the Developed Washing Machine Laboratory Model

The initial performance effectiveness study aimed to illustrate the precision of the developed device model and the validity of the design in terms of the correct implementation of the RFID system in the laboratory model of a washing machine built to create a measurement environment for the designed textronic RFIDtex transponders. During the tests, several assumptions were made. Cotton fabrics with sewn RFIDtex transponders were used in the tests. The drum of the model was completely filled with fabrics equipped with transponders. The identification of groups of transponders was carried out during movement of the drum, thus simulating the conditions in the washing machine drum. In the developed model, there was no water in the drum. During the scanning process, the drum was rotated to ensure that each of the textile-integrated identifiers would be as close as possible to the antenna array of the RWD for a specified period of time.

The tests were carried out in an anechoic chamber (Figure 11) to create a noiseless environment and avoid the influence of electromagnetic disturbances on the tested device. The use of RFID technology required appropriate technical solutions and materials to propose a demonstration work environment of the RFID system free of the influence of metals on the process of reading the serial number of RFIDtex transponders, as well as obtaining the appropriate interrogation zone. Device tests were based on performing a scan that consisted of reading of the serial numbers of transponders. The data were then processed by the microcontroller and stored in the system memory.

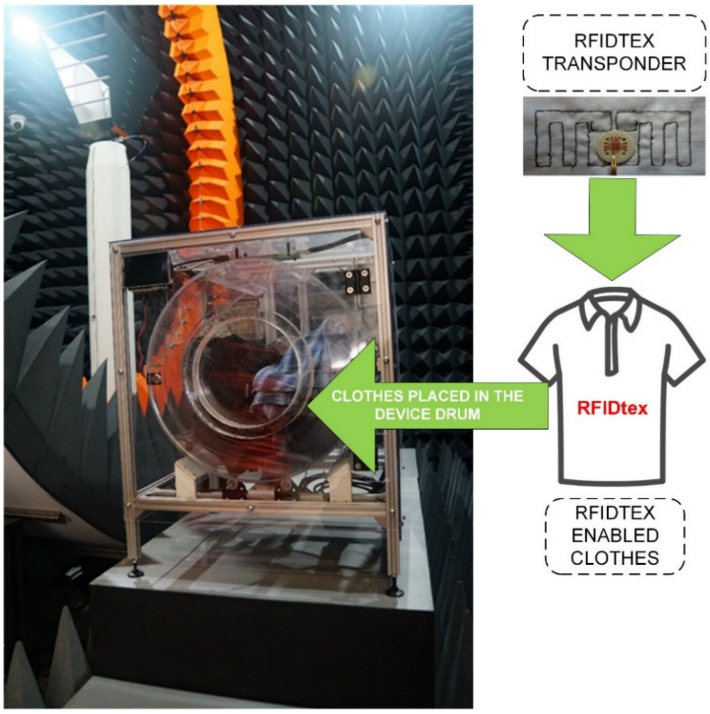

Figure 11. Developed device test stand.

As part of the tests, the identification process was carried out in the range of one to thirty transponders. For each identification attempt, a predetermined number of transponders, ranging from 1 to 30, were placed in the drum of the developed device, and five attempts were made to read the group. Based on the number of correctly read transponders in each sample, the average number of identifications in five trials and the percentage effectiveness of identifying a group of transponders were determined.

Due to the fact that the FEIG read/write device used in the device was equipped with the function of multiple reading of the group of transponders, it was used to increase the efficiency of the model. The developed control software saved in the memory of the microprocessor system the result of the set sequence of readings of the group of transponders and then dynamically built the list of read transponders. Due to the implementation of this functionality, it was possible to increase the efficiency of reading the group of transponders, which was proved by repeating the identification process in the range of two to six readings of the group of transponders. These attempts were also repeated five times. Duration of scans was adjusted dynamically thanks to the abilities of ISO18000-63 protocol.

The measurement results obtained (Figure 12) prove the correct operation of the designed and constructed laboratory demonstrator. Even with a single scan that included the identification of a group of objects equipped with transponders, the system showed a high reading efficiency (in the order of 100%) of up to 15 objects in the drum. Increasing the number of scans caused the identification efficiency of 100% to be achieved even if there were up to 22 objects in the drum. The measured group identification efficiency dropped the fastest when using only one scan, and for 30 objects in the drum, it was only 46%. In the case of a group scanned six times, the efficiency with even 30 objects in the drum remained at the level of 90%. This showed that it is possible to effectively use RFID systems and RFIDtex tags in laundry technology.

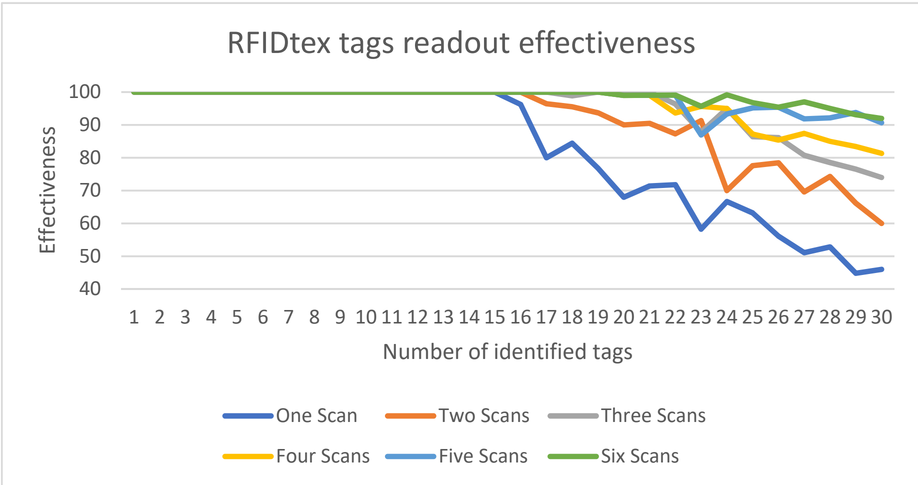

Figure 12. Developed device effectiveness as a function of the number of identified objects.

9. Conclusions

The subject of this study was the construction of a demonstration model of a washing machine that uses radio object identification technology to carry out research on the effectiveness of selected RFIDtex transponders in the field under study. The model was designed and built to simulate the real operation of a laundry appliance for self-identification of the contents of the drum. The identification process was done using the built-in read/write device.

In the implementation of the model, several assumptions were made that influenced its design. The model's task was to enable laboratory tests of RFIDtex tags developed as part of the work carried out at the Rzeszów University of Technology by providing a working environment similar to a real automatic washing machine. The drum of the constructed model enabled the identification of groups of transponders during its movement, thus simulating the conditions in the washing machine drum. In the developed model, the drum was not filled with water. This decision was made because the entire process of identifying objects in the drum and possible removal of clothes from inside the drum, the parameters of which when read from the memory of textronic RFID transponders make it impossible to choose the right washing program, took place before filling the drum with water and start of washing program.

The developed and built model was subjected to a series of tests that showed efficient identification of transponders inside the drum. As part of the work, device management software with the appropriate communication model was also developed. All aspects of the operation of the control algorithms that ensure high efficiency of the model, together with the appropriate communication model, will be presented in a separate publication with a detailed description of developed software algorithms.

The developed device demonstrates an innovative approach to the process of washing textiles controlled by information read from innovative RFIDtex transponders sewn into the fabrics. It may be used as a basis for building a fully functional prototype of an automatic washing machine that uses information stored in the memory of RFID tags to control the washing process.

It should be emphasized that the use of information about the parameters of fabrics may allow for a completely new approach to controlling the washing process. It also opens up completely new research fields, among which it is worth mentioning the aspects related to controlling the washing process including selecting the best washing program for many fabrics at the same time, controlling the processes of automatic detergent dosing, controlling the rotation speed of the drum and temperature changes in the drum during the washing process, and the impact of the entire control process on the consumption of water, electricity, and detergents by washing machines.

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Appendix A

Communication between the microcontroller and the RWD consists of sending properly prepared commands in the form of frames sent through the RS232 port. They are written to the RWD configuration memory, which is organized into 16-byte configuration blocks. They are subdivided into 14-byte blocks of configuration parameters and 2-byte CRC16 checksums. After sending the appropriate data frame, the microcontroller listens to the RWD response and compares it with the expected correct response. The selected commands are listed in Table A1.

Table A1. Selected read/write device commands.

Command	Byte/Value	Description
STX	0/0x02	Start of communication
MSB ALENGTH	1/0x00	Data frame length MSB
LSB ALENGTH	2/0x16	Data frame length LSB
COM-ADR	3/0xFF	Device address
CONTROL-BYTE	4/0x81	Command definition
STATUS	5/0x81	Data status
BAUD	8/0x0A	Interface speed
TRANSFORM	9/0x00	Data format definition
TR-RESPONSE-TIME	12–13/0x01/0x2C	Max command duration
POWER-ON-MODE	14/0x00	RWD behavior after power on
PROTOCOL MODE	15/0x00	
SCAN-INTERFACE	17/0x00	Defines communication port for scan mode
INTERFACE	18/0x95	Communication ports flags
READER-MODE	19/0x80	Defines RWD work mode
CRC16	20–21/dynamic	Cyclic redundancy checksum

There are three main modules distinguished in the developed device software (Figure A1). The main module of the washing machine demonstrator is "Start washing", which performs the function of reading multiple RFIDtex transponders simultaneously. It allows the user to view the recognized contents of the transponder memory and supports the decision to select a washing program. The RWD "Buffered Read Mode" operation mode is required for the operation of the above-mentioned module.

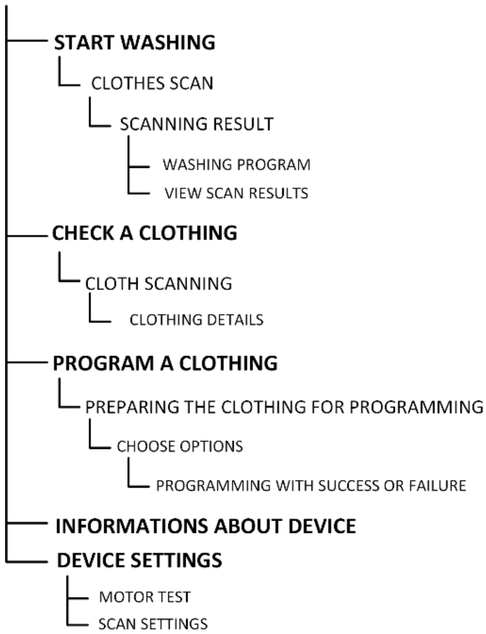

Figure A1. Structure of the software developed for the device.

Another software module of the system is the transponder programming module called "Program a Clothing". Programming consists of the appropriate upload of product data to the transponder memory. The read/write device's "Host Mode" is used for this purpose.

The last module is a quick single-cloth (transponder) check. The RWD with the enabled "Scan Mode" operating mode set is still waiting for the transponder, and after reading it, it sends its data via the communication interface to the STM32 microcontroller to display data on the LCD screen (Figure A2). The SPI (serial peripheral interface) is used for communication between the display and the microcontroller. The display is connected in a four-wire configuration. This means that the software automatically separates the data bytes between the I/O lines using the same bit pattern. The motor is controlled by the controller by giving it the appropriate PWM signal (pulse-width modulation).

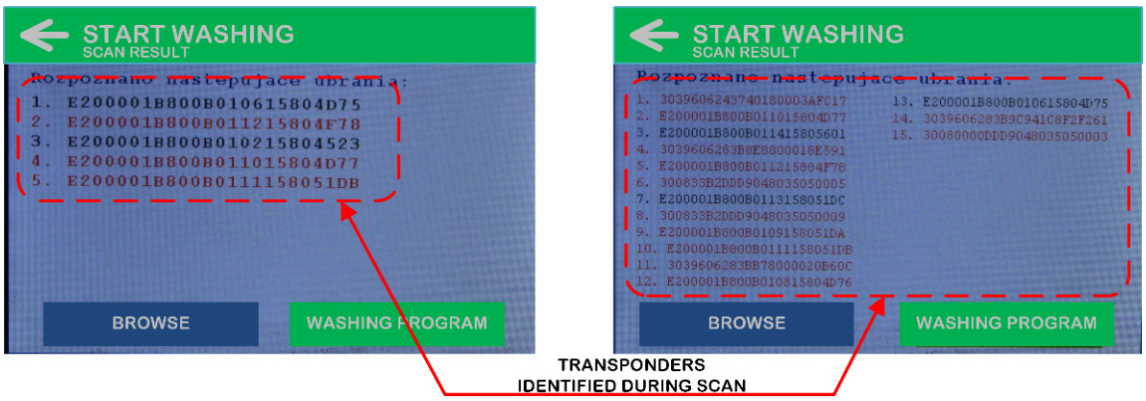

Figure A2. List of read transponders.

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