An Innovative Portable Device for Diesel Engines and Transmission Electronic Control Units Diagnosis and Debug

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***Abstract*—Heavy-duty construction machinery together with all the diesel engine-based vehicles, as those used for logistics and transportation, are of paramount importance for the economy in both developed and under development societies. Despite the strong interest in e-mobility recently, it is practically very difficult to replace diesel engine-based vehicles by electrical alternatives specifically for application domains associated with logistics and heavy construction works. Traditionally, these vehicles are characterized by high costs of investment and ownership, expensive repair and maintenance services and requirement for high operational availability. This paper presents the design of a portable that allows the diagnosis and debugging of electronic control units of transmission systems as well as diesel engines. Amongst the most advantages of this device are the capability of effective service in-situ and its versatile support of all the existing commercial transmissions and diesel engines. Moreover, the total repair cost and time are significantly decreased.**

Keywords—electronic control unitl; heavy-duty construction machinery; portable device; transmission; solenoides drive; embedded systems.

I. Introduction

Typically, in heavy-duty construction machinery there are two types of electronic control units (ECU), one for the diesel engine and another one dedicated to the transmission control. Table 1 presents the market ecosystem regarding the manufacturing of transmissions and diesel engines. These solutions, in various combinations, are used by all the vehicles manufacturers worldwide.

TABLE I. Existing Transmission and Diesel Engines Manufacturers

Manufacturer	***Engine***	***Transmission System***
Caterpillar	√	√
Volvo	√	√
ZF	-	√
Cummins	√	-
Detroit Diesel	√	-
Allison Transmission	-	√
Komatsu	√	√

Manufacturer	Engine	Transmission System
Carraro	-	√
DANA	-	√
Perkins	√	-
International	-	√
Voith	-	√
Deutz	√	-

The ECUs installed originally by the vehicles' manufacturers are interconnected with either the engine of the transmission system through specific wiring harness and automotive connectors. Via this cabling ECU interconnects with the variety of sensors and actuators embedded in the controlled system. Unfortunately, these schemes don't comply with any standard and are different amongst the vehicles' manufacturers. This implementation pluralism many times imposes a high complexity in general service stores resulting in service delays and setup expenses.

The proposed device comes to support technicians and engineers to troubleshoot and repair diesel engines and transmission systems. It can bypass the existing original ECUs in order to take control over and perform targeted or generic operations concluding so for any malfunction.

The hardware and software design of the portable device is described in the following sections.

II. Device's Architecture

Having studied thoroughly the existing technical resources from key market manufacturing companies and combing experience in repair and maintenance practice for the last two decades the architecture for ideal portable diagnosis and debugging device was configured and it is illustrated in Fig. 1 [1] – [11].

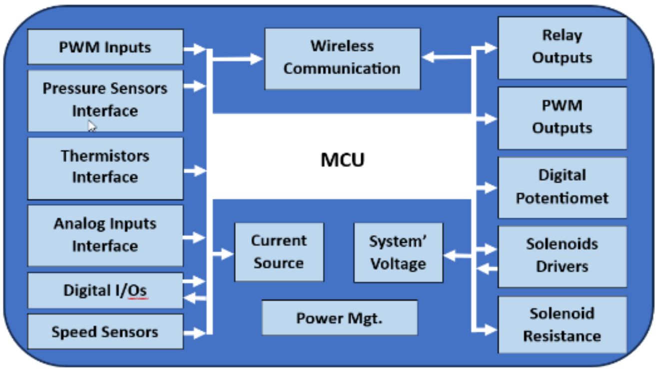

Fig. 1. *The architecture of the proposed portable device*

Next, it was decided that the device should have the features mentioned in Table 2 so as to act as functional superset in order to effectively support any kind of transmission, diesel engine or even single sensors and actuators. With capabilities, the device may be considered as an agnostic ECU.

TABLE II. Features of the Proposed Portable Device

Feature	Type	Quantity
Solenoids	Output	15
Analog	Input	2
Digital Potentiometers	Output	2
GPIO	Input / Output	10
Pressure Sebsirs	Input	16
Speed Sensors	Input	5
Beeper	Output	1
Relay Contacts N.O/N.C.	Output	3
Optocoupler	Output	2
PWM	Input	4
Thermistors	Input	2
1-Wire	Input / Output	1

III. Hardware Design

The description of the hardware design includes the design of the circuits of the sub-systems and the design of the printed circuit board (PCB) of the device. For both design works, considerations such as the end users' particular requirements, operation environment, total production cost, robust semiconductors solutions, and form factor were taken into account. Actually, the second version of the device is presented here. First version was designed and tested in the field in various transmission systems and it was enriched with additional circuitry as well as some circuits were replaced by more efficient ones.

A. Schematic Design

In the next subsections the most critical sub-circuits of the portable device are described. Plain circuitry are omitted from the report.

1) Microcontroller Unit

The most critical component of the system is the microcontroller unit (MCU) which interconnects with all the signals from all the sub-systems circuits.

Specifically, an ARM 32bit Cortex-M4 with 512k of Flash and 128k RAM memory. The STM32F446Z from ST Microelectronics is a 144 pins surface mount device (SMD) and it is illustrated in Fig. 2.

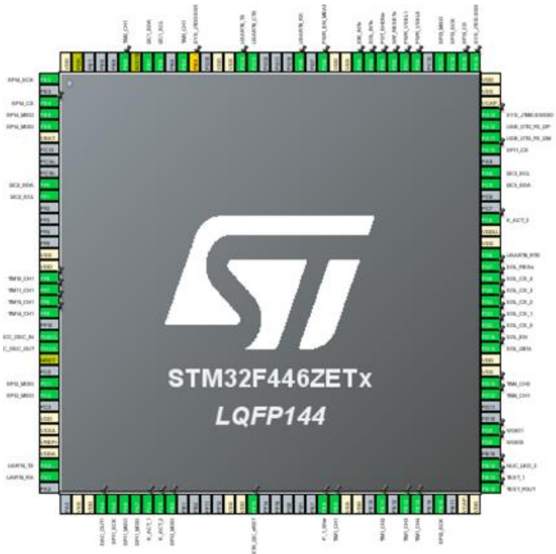

Fig. 2. *The microntroller used in the device*

The schematic design of the MCU is shown in Fig. 3.

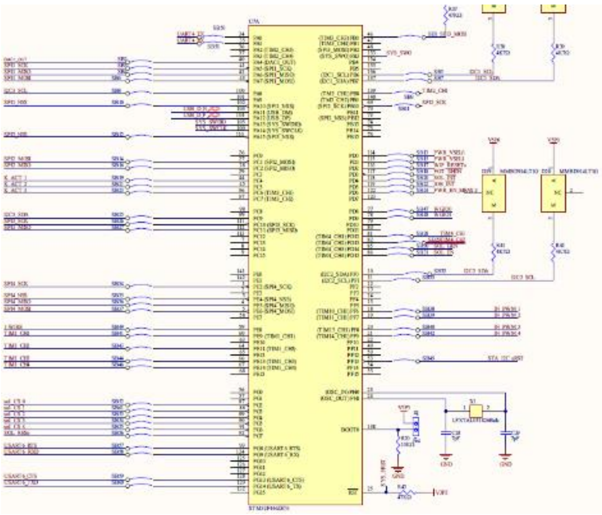

Fig. 3. *The microntroller's schematic circuit*

2) Power Management

The portable device has been designed so as to support either 12Vdc or 24Vdc systems. For this reason, it can be powered by one of these voltages either from a battery or from a stationary power supply. In any case, the external power voltage is converted to 12Vdc. Specific protection circuitry has been used to avoid using both voltages simultaneously.

Fig. 4 presents the circuits used for power management. Specifically, +3.3Vdc and +5.0Vdc voltages are generated to cover the energy needs of all the logic circuits. In addition, two voltage references for external devices are designed.

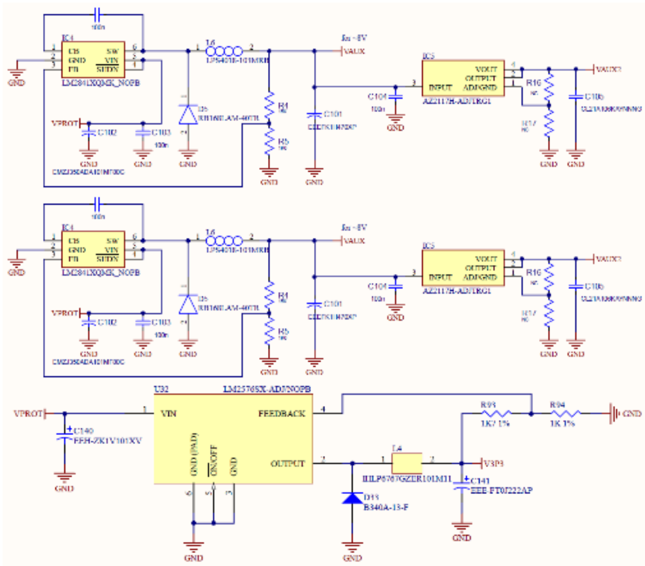

Fig. 4. *Power management circuits design*

3) Digital Inputs and Outputs

To enrich MCU capabilities for general purpose digital inputs and outputs, the I/O extender TCA9535 from Texas Instruments has been incorporated into the design. The provided I/Os are of 5Vdc. MCU controls the functions of the extender through I2C bus interface. One of the outputs provided by the extender is used to drive external beeper devices for the case where an engine engages the reverse gear. Fig. 5 shows the signal conditioning for I/Os.

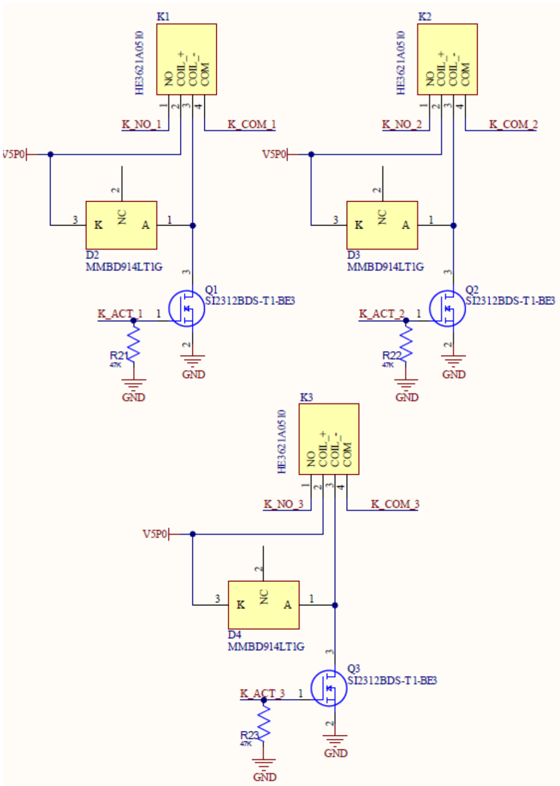

Fig. 5. *Power management circuits design*

4) Analog Inputs

The analog to digital conversion of external signals connected to the device is achieved using 12-bit ADC circuitry based on external +3.0Vdc reference voltage. The MCU controls the ADC circuitry via SPI interface (Fig.6).

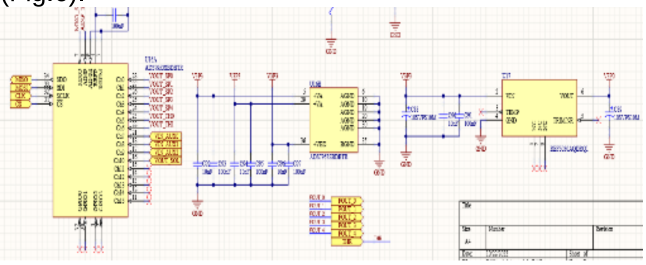

Fig. 6. *Reading analog inputs circuitry*

5) Thermistors Inputs

Reading temperature is a critical function of the device. Typically, thermistors are the most common type of components used in automotive domain. They change their resistance value according to the temperature. To allow for the most accurate measurements, the device employed specific circuits to provide constant current sources and create four different ranges. The constant current sources circuitry is described in a section below. Fig. 7 shows in detail the aforementioned circuitry for thermistors interfacing and reading.

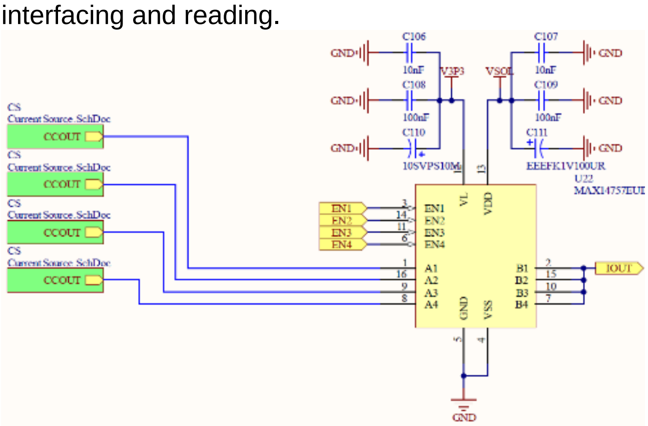

Fig. 7. *Thermistors input circuitry*

6) Pulse Width Modulation Inputs

Fig. 8 presents the specific circuitry designed to allow for interfacing the device with input signals of PWM type coming externally from the system under test.

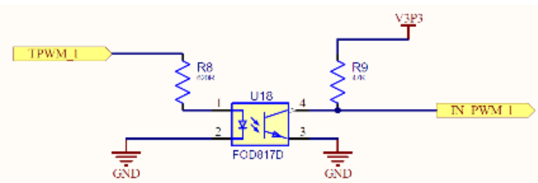

Fig. 8. *Pulse Width Modulation (PWM) inputs interface*

7) Pressure Sensors

Fig. 9 presents the design of the pressure sensors inputs' circuitry. Specifically, this is one of the multiple circuits of such type integrated into the design. A low-pass filter is used to immune electronic noise while a clumping circuit helps to keep signal below +3.3Vdc as well as to protect from any negative input voltages.

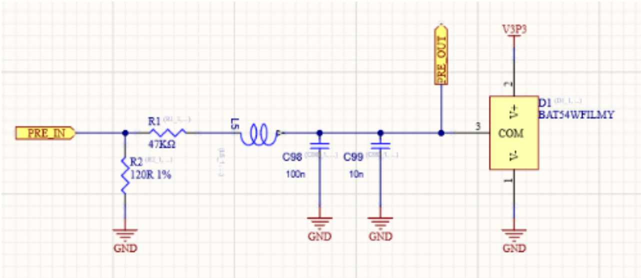

Fig. 9. *Pressure sensors inputs circuitry*

All the pressure sensors inputs are connected to an 12-bit ADC chip that is controlled by the MCU through SPI interface (Fig. 10).

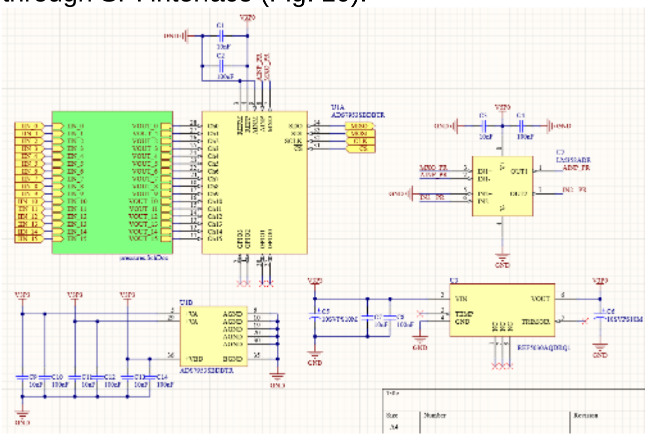

Fig. 10. *Pressure sensors inputs conversion to digital signals*

8) Soeed Sensors

The proposed device is allowing the connection of all the available types of speed sensors which are used in heavy-duty machinery. Fig. 11 illustrates the input signals conditioning and conversion to signals readable from the MCU.

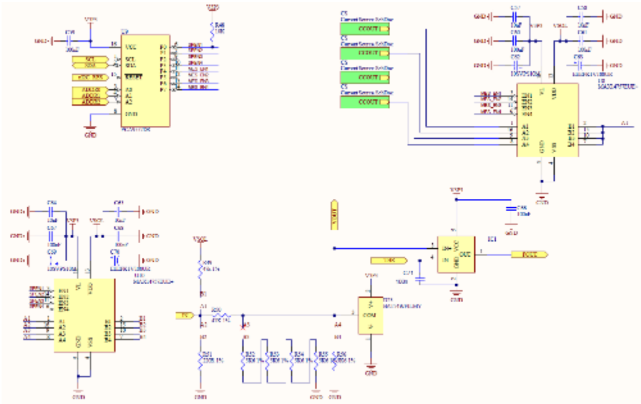

Fig. 11. *Speed sensors interface circuitry*

9) Digital Potentiometers

In order to exert control over the throttle of the engine under test, two outputs of variable resistance are employed in the design. Specifically, MCU through SPI interface controls the resistance output of two digital potentiometers (Fig. 12).

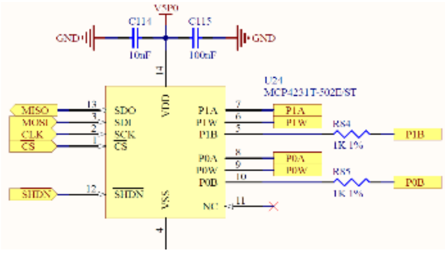

Fig. 12. *Digital potentiometers circuitry*

10) Current Source

Fig. 13 presents the design of the circuits for the constant current sources' generation. Because such circuits suffer from temperature, temperature compensation is provided by the designed circuitry.

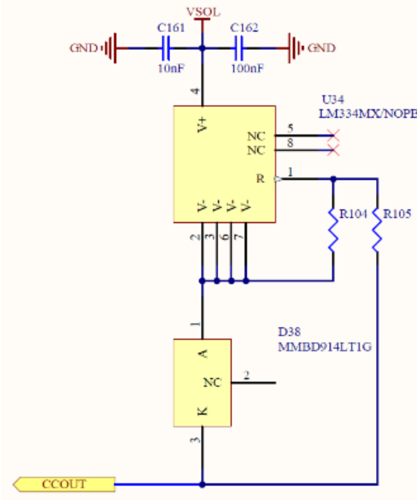

Fig. 13. *Current sources generatopn circuitry*

11) Wireless Communication

The proposed portable device allows for wireless connectivity to support the development of various human-machine interfaces. To increase flexibility and versatility, a connector is placed in the device in order to connect there any wireless module chosen now or in the future. This approach saves unwanted PCB redesigns every time that a new wireless module must be used. This connector is interfaced with the MCU using a Universal Asynchronous Receiver Transmitter (UART) to serial converter support speed up to 256kbps. Typical wireless modules that could be connected to the device would add WiFi or Bluetooth connectivity (Fig. 14).

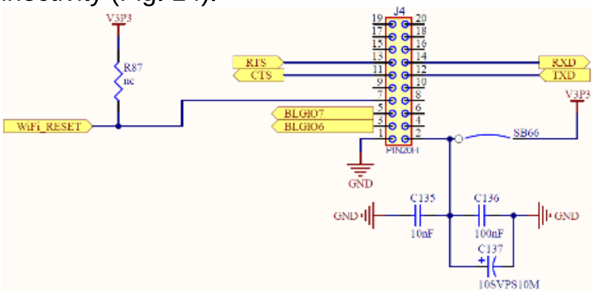

Fig. 14. *Wireless communication circuitry*

12) Solenoids Drivers

Maybe the most critical and difficult to design is the solenoids driver circuitry due to the variability in solenoids' types and functions. Through the control of the solenoids, the portable device is able to exert control over the operation of the transmission systems. On-off, Common-High, Common-Low and Floating are the solenoid driving modes supported by the designed circuitry presented in Fig. 15.

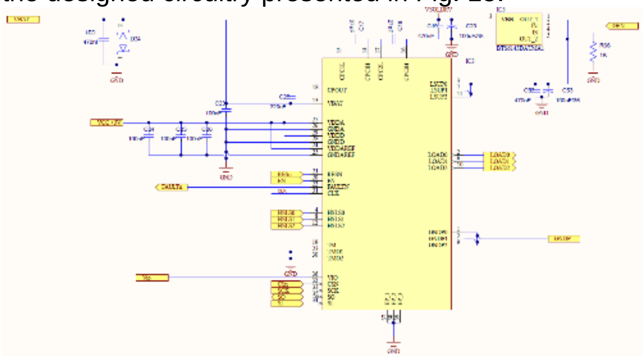

Fig. 15. *Solenoids driver circuitry*

The solenoids subsystem includes five TLE82453 integrated circuits from Infineon (Fig. 16). Each chip can drive three distinct solenoids. In total, fifteen different solenoids can be controlled simultaneously by the MCU. The interfacing between MCU and each one the five solenoid driver chips is taking place through SP port.

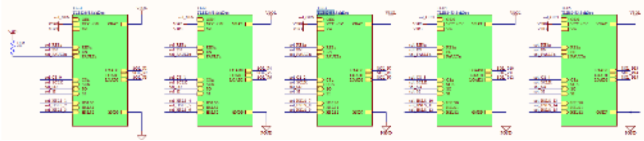

Fig. 16. *Five 3-channel solenoids drivers circuitry*

13) Physical Connectoms

To enable physical connections to external systems specific automotive connectors are used as these imposed by the transmission and diesel engines manufacturers. This portable device provides every input, output, control, and power signal to two connectors as it is depicted in Fig. 17. To allow connectivity with a variety of different systems, harness adaptors must be used.

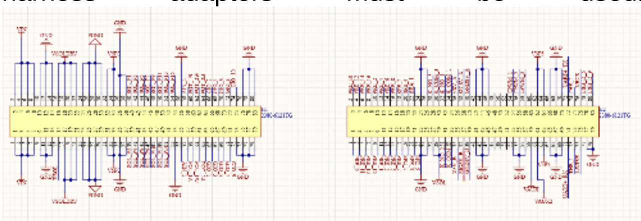

Fig. 17. *Signals' physical connetors*

B. Printed Circuit Board Design

After designing the circuitry of the subsystems, the design of the printed-circuit board (PCB) was designed. All the electronic components were selected in surface-mount type (SMT) where this was possible to decrease the physical dimensions of the produced PCB. The size of the PCB is 30.15cm x 18.23cm.

To ensure size minimization as well as the most effective electromagnetic immunity, PCB was designed as a six-layer board (Fig. 18 – Fig. 25).

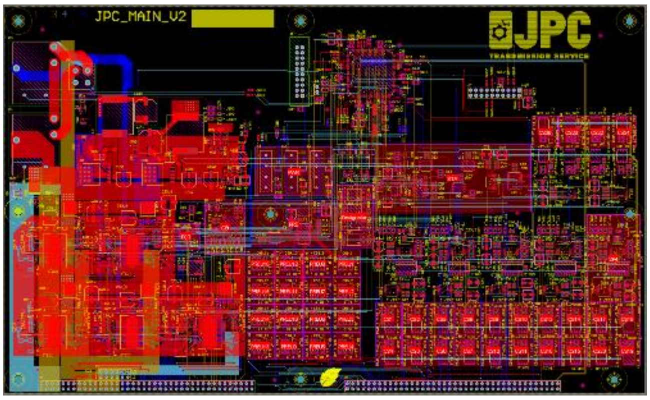

Fig. 18. *Overal view of the 6-layer PCB*

Fig. 19. *Three-dimentional representation of the PCB*

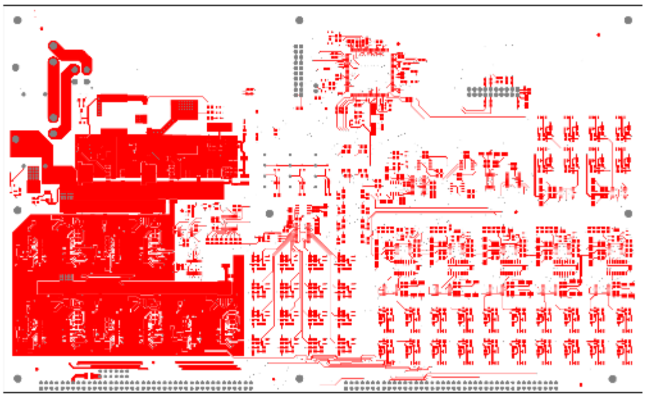

Fig. 20. *Top layer of the PCB*

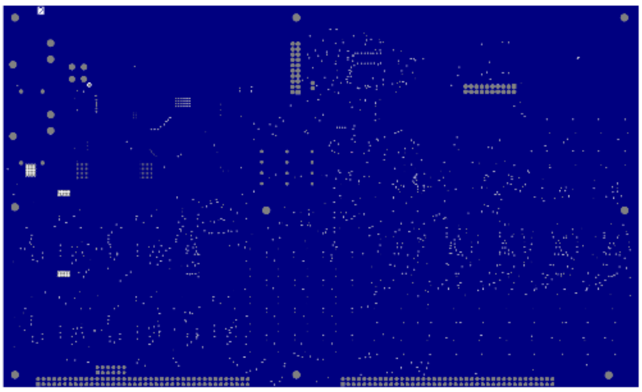

Fig. 21. *Ground plane of the PCB*

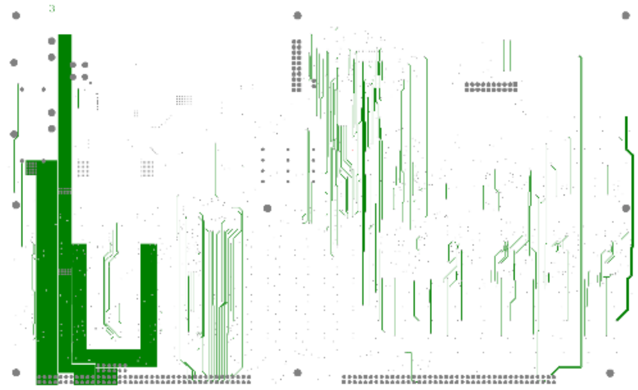

Fig. 22. *Vertical signals' routing layer of the PCB*

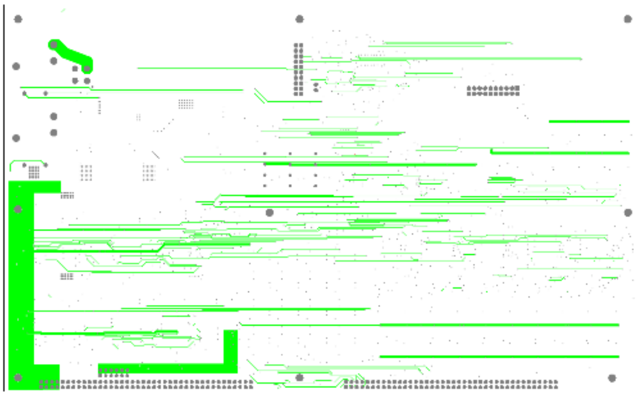

Fig. 23. *Horizontal signals' routing layer of the PCB*

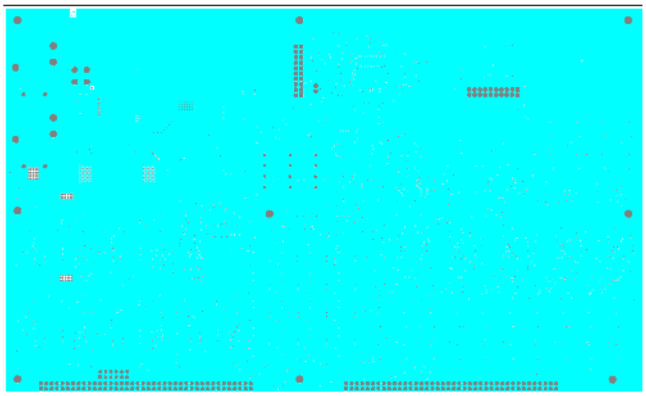

Fig. 24. *Power plane of +3.3Vdc of the PCB*

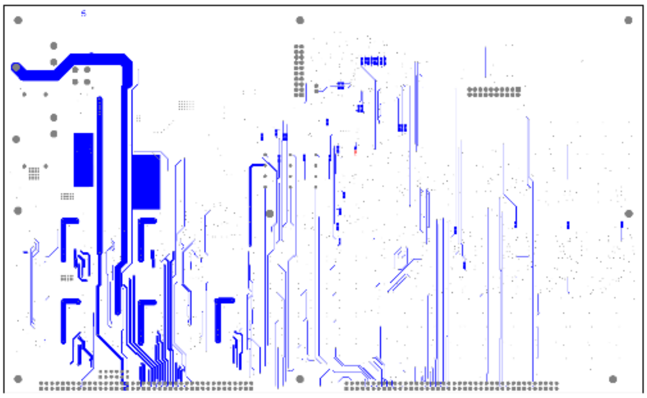

Fig. 25. *Bottom layer of the PCB*

Next, a specific PCB was designed to allow for the soldering of two automotive-type connectors through which all the signals from and to the device can be reached. Fig. 26 and Fig. 27 illustrate the four-layer

PCB and a three-dimensional representation of this connections board. The size of this board is 30cm x 7.5cm.

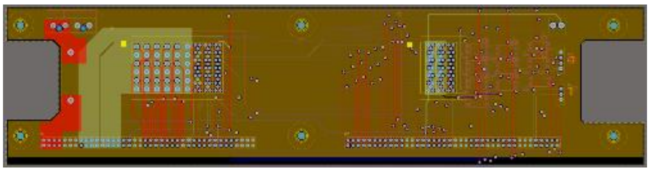

Fig. 26. *Four-layer PCB of the cobbections board*

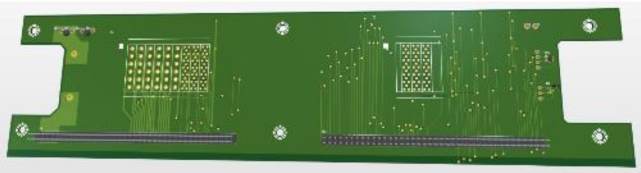

Fig. 27. *Three-dimensional representation of the connections board's PCB*

IV. FIRMWARE DESIGN

The firmware of the MCU was built using the Integrated Development Environment (IDE) provided by ST Microelectronics. Code was written in C language. The FreeRTOS operating system (OS) was used to keep the control and synchronization of every single task performed by the MCU.

A custom Application Programming Interface (API) was devised in order to support the communication between the device and any external Human-Machine Interface device i.e. smart phone or table. The communication fashion is based on the issue of API-compatible commands from the HMI device to the device and return answers with information from the device. In this way the scenario of the control and HMI is entirely placed in the HMI's side and not in the MCU of the device. This minimizes firmware upgrades and modifications during the life cycle of the device.

V. HUMAN-MACHINE INTERFACE

After having completed the hardware design of the portable device, and after performing the necessary components soldering and static stimulus testing of the circuitry, the HMI was designed. The first attempt of the HMI design waw realized using LabVIEW. This option had the advantage of quick and targeted implementation to test every single function of the device. This approach practically was very helpful during the design and development of the first version of the device. Fig. 28 illustrates a view of one of the many front panels designed in LabVIEW for testing purposes.

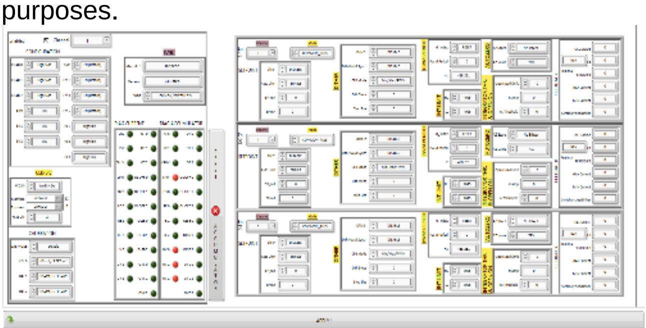

Fig. 28. *LabVIEW front panel view for testing of the device*

VI. FIRMWARE DESIGN

In parallel with the hardware design of the second version of the portable device, the HMI was designed using this time the framework of React Native. The aim of this choice was to be able to built cross-platform HMI applications to agnostically support mobile computing devices with IOS or Android operating systems.

Fig. 29 and Fig. 30 give a view of the dedicated HMI screens for transmission systems and diesel engines respectively.

Fig. 29. *HMI sceen for transmission systems diagnosis and debug*

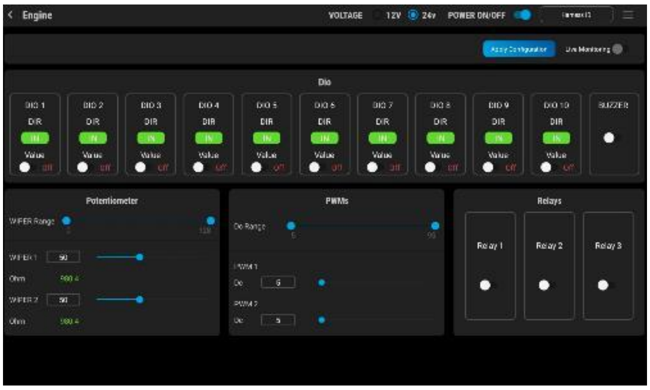

Fig. 30. *HMI screen for diesel engines diagnosis and debug*

VII. IMPLEMENTATION AND TESTING

The last step of the design of the portable device was to produce the necessary variety of automotive harness to allow for straightforward connection to existing diesel engines and transmission systems. Next, a sound range of tests using real-world systems in the service premises was undertaken. Table 3 shoes the combinations made using market parts and systems.

TABLE III. TESTING COMBINATIONS USING MARKET COMPONENTS

Allison 3000 WTEC III	
Solenoid Type 1	2x 29536722
Solenoid Type 2	4x 29537371
Solenoid Type 3	1x 29545638
Speed Sensor Type 1	2x 29543432
Speed Sensor Type 2	1x 29543433
Analog sensor (Oil Level)	29530105
Allison 3000 WTEC IV	
Solenoid Type 1	2x 29541897
Solenoid Type 2	4x 29544297
Solenoid Type 3	1x 29545638
Speed Sensor Type 1	2x 29543432
Speed Sensor Type 2	1x 29544139
Analog sensor (Oil Level)	29549755
Allison 8000 CEC2	
Solenoid Type 1	9x 23019734
Speed Sensor Type 1	3x 29543432
Dana T12000	
Solenoid Type 1	4x 4201576
Speed Sensor Type 1	2x 4204285
Dana TE27000	
Solenoid Type 1	4x 4304124
Solenoid Type 2	3x 4216197
Speed Sensor Type 1	2x 4209752
Speed Sensor Type 2	1x 4209750
Analog sensor (Oil Level)	1x 501317160
ZF 3WG151	
Solenoid Type 1	5x 501313374
ZF 4WG65	
Solenoid Type 1	4x 501319202
Solenoid Type 2	1x 501310470
Solenoid Type 1	1x 501317160
Solenoid Type 2	1x 501317159

Fig. 31 demonstrates the portable device used to test a Cummins diesel engine.

Fig. 31. *Testing a Cummins diesel engine*

Fig. 32 demonstrates the portable device used to test a Volvo L120H2 transmission system.

Fig. 32. *Testing a Volvo transmission system*

Fig. 33 demonstrates the portable device operated in the field inside the operator’s cabin of a Dumper Terex.

Fig. 33. *Testing and control a Dumper Terex in the field*

VIII. CONCLUSIONS

The design of a portable device for diesel engines and transmission systems diagnosis and debug was presented covering all the steps associated with the theoretical design of the circuitry, the design of the PCBs, the firmware development, as well as the design of the HMI software applications.

According to the several tests taken place either in the lab or in the field, it can be safely stated that this device is very versatile and robust allowing end users to overcome complexity and time delay inherent in the testing of heavy-duty constructions machinery.

ACKNOWLEDGMENT

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