

LESZEK KASPRZYCZAK*¹, ROMAN PIETRZAK***ELECTROMAGNETIC COMPATIBILITY TESTS OF MINING MOBILE INSPECTION ROBOT****BADANIA KOMPATYBILNOŚCI ELEKTROMAGNETYCZNEJ GÓRNICZEGO MOBILNEGO
ROBOTA INSPEKCYJNEGO**

The article presents the methodology and results of electromagnetic compatibility tests conducted on a non-commercial prototype of the Mining Mobile Inspection Robot. The tests were carried out in an accredited laboratory of the Institute of Innovative Technologies EMAG in compliance with European standards harmonized with the 2004/108/EC (EMC) directive. In the article the testing stands were characterized along with the test types, performance criteria and test results. The testing methodology and the selection of standards can be a pattern to conduct electromagnetic compatibility tests for similar products designed for the mining industry.

Keywords: mining robot, electromagnetic compatibility tests and requirements

Przedstawiono metodykę i wyniki badań kompatybilności elektromagnetycznej niekomercyjnego prototypu Górniczego Mobilnego Robota Inspekcyjnego. Badania te prowadzono w akredytowanym Laboratorium Instytutu Techniki Innowacyjnych EMAG wg europejskich norm zharmonizowanych z dyrektywą 2004/108/EC (EMC). Scharakteryzowano stanowiska badawcze, rodzaje badań, kryteria oceny oraz wyniki badań. Metodyka badań oraz dobór norm mogą posłużyć jako wzór do prowadzenia badań na kompatybilność elektromagnetyczną podobnych wyrobów przeznaczonych dla górnictwa.

Słowa kluczowe: górniczy robot, wymagania i badania kompatybilności elektromagnetycznej

1. Introduction

The non-commercial prototype of the Mining Mobile Inspection Robot (GMRI) was developed in a R&D project financed from the state budget by the National Centre for Research and Development. The project was carried out by the Institute of Innovative Technologies EMAG and the Industrial Research Institute for Automation and Measurements PIAP.

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GMRI has been designed to monitor areas with gas and/or coal dust explosion hazards in hard coal mines. Such zones are the longwall areas where – with some coal remaining in goafs – there are fire hazards and real fires happen sometimes (Cioca & Moraru, 2012). Such situations occur from the properties of coal in the given bed (Trenczek, 2008). Therefore, practically almost every exploitation area can be isolated due to such reasons and then monitored.

The robot can be used to inspect isolated excavations or can make measurements for rescue teams to inform them in advance about the conditions in the area.

In the papers published so far (Kasprzyczak et al., 2009, 2012, 2013; Kasprzyczak & Trenczek, 2011) the authors discussed in details the functionality of the robot, its kinetic system, pneumatic drives, sensor systems for monitoring concentrations of gases, temperature and humidity, electrical and pneumatic power supply systems, explosion-proof solutions compliant with the 94/9/EC (ATEX) directive and harmonized standards, traction tests of the robot in a real mining excavation conducted by the Mining Rescue Centre Co. and on testing ground, and, finally, metrological tests of the measurement system. Additionally, the work (Kasprzyczak et al., 2012) presents a review of mining robots in the world.

Figure 1 shows the GMRI robot and the operator's stand. The stand comprises a computer with higher resistance to dust and water ingress with IP54, as well as the resistance to stronger vibrations and shocks. The computer has been equipped with software for controlling the robot and visualizing the measurements from sensors and images from cameras. The robot can be controlled by means of a joystick, mouse or touch-screen. In order to separate non-intrinsically safe circuits of the computer from intrinsically safe circuits of the robot, the operator's stand has been equipped with a power, transmission and separation device PTSD.



Fig. 1. GMRI robot and operator's stand

In this article the authors focused on discussing an EMC testing methodology applied in tests conducted by the Electromagnetic Compatibility Laboratory of the EMAG Institute. Before the tests were launched, there had been some standards analyzed along with recognized publications

about EMC phenomena (Ott, 2009; Williams, 2001) and regulations of the European Union. The analyzed standards were EN 50270, EN 61000-4-1 and EN 61326-1. It was found out that EN 50270 cannot be applied in scientific or laboratory apparatus used for analyses or measurements. However, it can be supportive to determine the requirements concerning the working accuracy of measuring sensors. Whereas EN 61326-1 elaborated by the Technical Committee on Industrial Automation and Robotics refers to electrical equipment for measurements and testing. This standard is used, among others, for equipment applied in industry. It comprises requirements concerning immunity and emission of electromagnetic fields for electrical equipment powered by voltage lower than 1000 V AC, to be used in the process industry, production and education, including equipment and computers for measurements and tests, control, laboratories, as well as industrial and non-industrial locations. The prototype of the Mining Mobile Inspection Robot has intrinsically safe circuits with low DC voltage. The PTSD device, in turn, is powered by single-phase voltage 230 V which, after being converted to intrinsically safe voltage, supplies the battery of the robot through a copper cable. The operator's measuring and control console in the form of a laptop and joystick is not subjected to assessment by this standard because computer appliances which are part of IT systems can be used without extra tests in the systems covered by EN 61326-1.

2. Equipment under test (EUT)

The mobile robot contains mechanical and electronic subassemblies. Figure 2 shows the diagram of the robot – its electronic systems are placed inside the frame marked ROBOT. The data flow is marked by a thick line, while electrical power supply by a thin dashed line. The robot comprises four programmable microcontrollers: MuC – main microcontroller of the robot, SuC sensors system of the robot, VC – valves controller of the robot, and a power distribution system equipped with an AuC – auxiliary microcontroller.

The frame marked OPERATOR'S STAND contains stationary systems available for the operator. These are: CMC – control and measuring console and PTSD – power, transmission and separation device with an intrinsically safe power supply device. The CMC console communicates in a bi-directional half-duplex mode with the MuC in a modem standard V.23 with one pair of cables. Then orders/queries/data are distributed from the main microcontroller to other programmable units of the robot. The VC – valves controller receives orders responsible for the movements of pneumatic actuators and receives signals from the sensors which give information about the state of the robot. The orders to trigger the measurements are sent to the SuC – sensors microcontroller, while measurement values are obtained from this controller. The auxiliary microcontroller placed in the power distribution system receives orders to turn on/off the cameras and lighting and gives measurement data indicating the charge level of the lithium-ionic battery. The data stream from the cameras is linked by another pair of cables straight to the PTSD separators in the RS485 standard. The CMC console, in turn, is linked to the PTSD separators by a USB cable.

The systems of the robot were divided into two intrinsically safe galvanically separated systems (marked with dashed and dotted frames). The first system is used for communication with the operator's stand and for measurements. It is powered by a nickel-cadmium battery. The second system, powered by a lithium-ionic battery (non-chargeable) is used, first of all, to supply power to coils of electro-pneumatic valves and cameras when the robot approaches the target area.

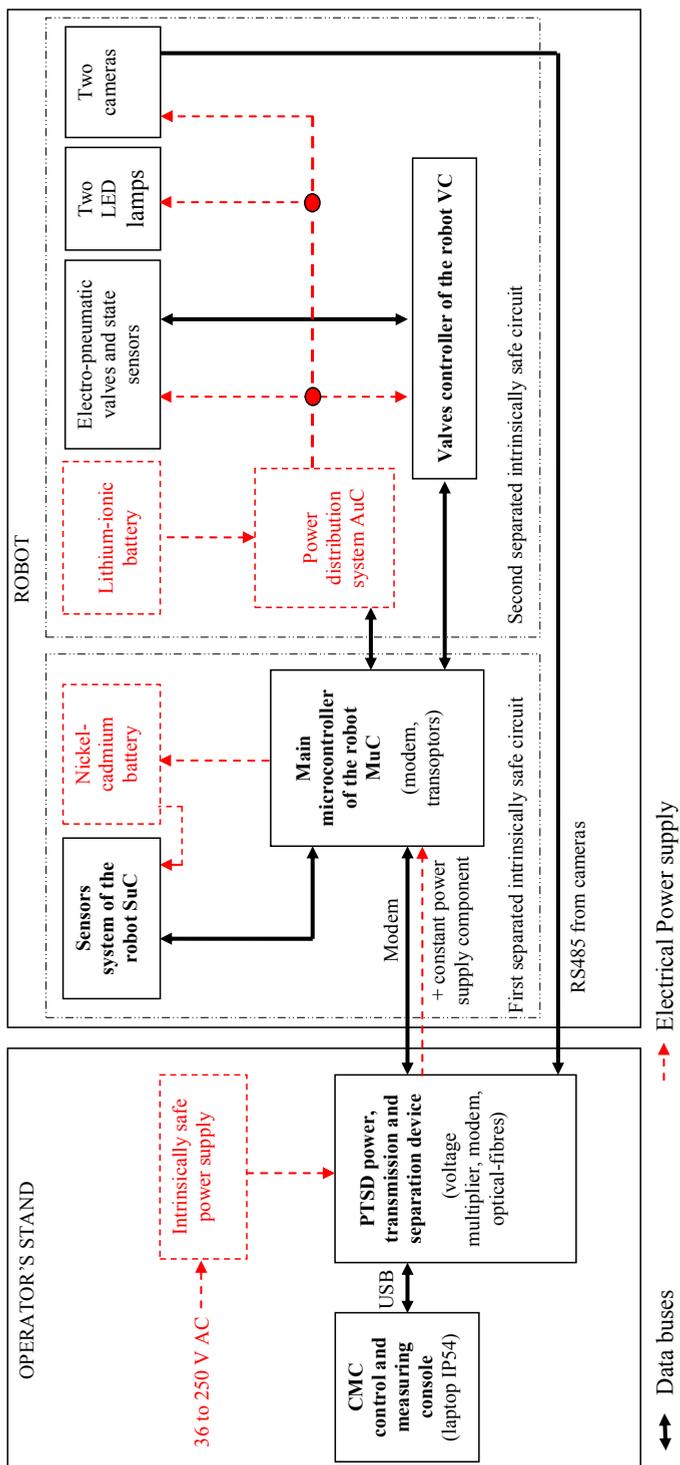


Fig. 2. Diagram of GMRI electronic circuits

3. Immunity tests according to EN 61326-1, item 6

Immunity tests were conducted according to Table 2 from the EN 61326-1 standard. The exposure was arranged according to basic standards from the IEC 61000-4 family summarized in EN 61000-4-1. Table 1 features the conducted tests.

TABLE 1

Immunity tests of the GMRI robot

Port	Disturbing phenomenon	Remarks
Enclosure port	Electrostatic discharge ESD	Not tested due to the assumed high humidity in the place of GMRI work.
	Radio-frequency electromagnetic field	10 V/m (80 MHz to 1 GHz)
	Power-frequency magnetic field	Not tested due to the lack of robot subassemblies vulnerable to this field.
AC Power port	Voltage dips	0% for 1 cycle (20 ms) 40% for 10 cycles (200 ms) 70% for 25 cycles (500 ms)
	Voltage interruptions	0% for 250 cycles (5 s)
	Fast transients	2 kV (5/50 ns, 5 kHz)
	Surges	Not tested due to the power supply of the operator's stand from a separated IT network of the mine.
	Radio-frequency common mode	3 V (150 kHz to 80 MHz)
Signal port	Fast transients	1 kV (5/50 ns, 5 kHz)
	Surges	Not tested due to the power supply of the robot from the intrinsically safe power supply with output voltage 12 V DC.
	Radio-frequency common mode	3 V (150 kHz do 80 MHz)

3.1. Electromagnetic field – enclosure port

Figure 3 presents the GMRI robot with the PTSD device in a semi-anechoic chamber, on a stand for testing immunity against the radio-frequency electromagnetic field. PTSD was powered with single-phase voltage 230 V from a connection placed inside the chamber. The operator's console was outside the chamber and was connected through a cableway with a USB cable. During the tests the pneumatic elements of the robot were powered from a bottle with compressed nitrogen in order to enable the observation of possible (undesirable) movements.

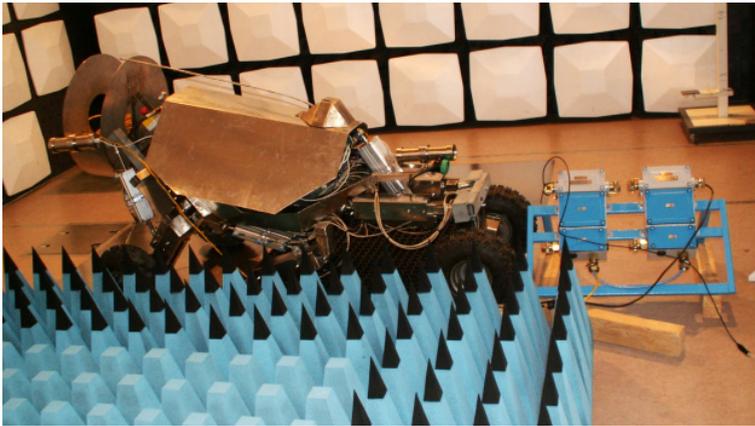


Fig. 3. GMRI and PTSD locations in the chamber during exposure to an electromagnetic field

Figure 4 features a diagram of the stand. The antenna which emits electromagnetic disturbances in the range 80-1000 MHz is static (vertical and horizontal polarization required). The tested object (EUT) is examined from all four sides. The exposed side of EUT lies in the facet of the uniform field. The cones on the floor prevent the field reflection from the floor.



Fig. 4. Simplified diagram of a stand for electromagnetic field exposure

The test was conducted to determine whether electronic circuits of the robot exposed to an electromagnetic field would work properly. The main assessment criterion of proper operations of the robot was the lack of uncontrolled movements of the robot organs during the test (the machine cannot be dangerous to people – please refer to the 2006/42/EC machinery directive). The observations were made with the use of a camera placed inside the chamber and connected with the monitor placed on the chamber operator's stand. There were no uncontrolled movements of the robot registered during the exposure.

Additionally, measuring accuracies of the sensors system were examined. The measurements were carried out with the use of “zero” gas (air) and calibration gases. For the “zero” gas and calibration gases the errors were the following:

- a) $\pm 5\%$ of the measuring range for methane,
- b) $\pm 10\%$ of the measuring range for carbon monoxide,
- c) $\pm 10\%$ of the measuring range for carbon dioxide,

- d) $\pm 2.5\%$ of the measuring range for oxygen,
- e) $\pm 1^\circ\text{C}$ for temperature,
- f) $\pm 3\%$ for relative humidity.

It was found out that the indication accuracy of gases concentration, temperature and humidity values is satisfactory and complies with the ranges given in Table 5 of EN 50270. The above results of testing measuring accuracy of sensors were achieved with grounded shields of electrical cables and grounded enclosures. With unconnected shields, in turn, the measurement results were unacceptably scattered.

3.2. Voltage dips – AC power port

Voltage dips on the AC power port were tested on the stand shown in Fig. 5 and 6. The robot was connected, through the PTSD device, with the generator of supply voltage (dips control device).

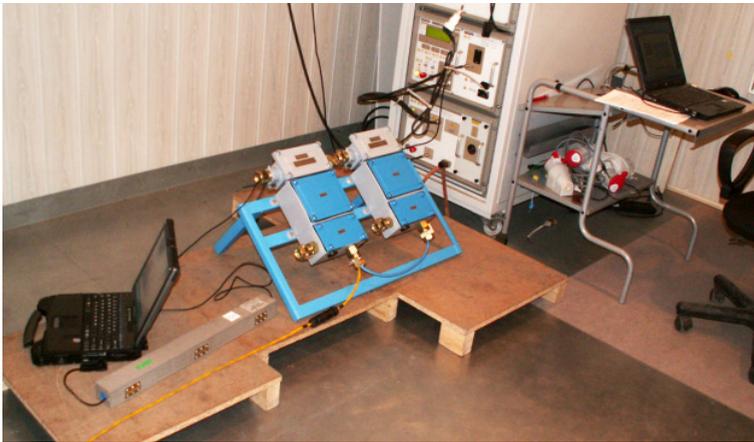


Fig. 5. The PTSD device (EUT) location on the stand for testing the immunity of the robot to voltage dips and interruptions

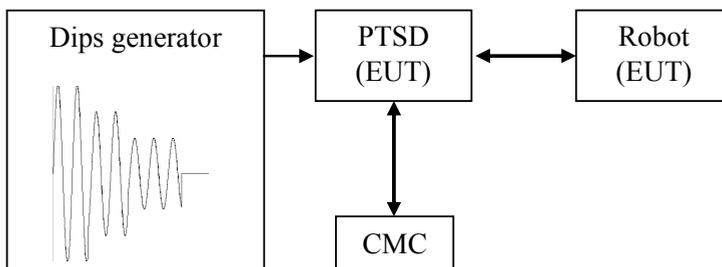


Fig. 6. Simplified diagram of testing GMRI immunity to voltage dips and interruptions

The EN 61326-1 standard puts the following quality criteria for EUT: criterion B for a 0% dip, criterion C for 40% and 70% dips.

The assessment criterion A indicates that the device should work without interruptions and according to its purpose during and after the tests. **The B Criterion** indicates that after the tests the device should work without interruptions and according to its purpose, while during the tests it is permitted to have worse functionality – down to the level accepted by the manufacturer. However, after the tests are completed, the device should return by itself to the condition it had before the tests. **The C Criterion** permits the situation that the device loses some functions during the tests, yet they can be recovered by the operator in a simple way.

Based on the observations made during the tests it turned out that the PTSD power supply, transmission and separation device of GMRI successfully fulfilled the above listed quality criteria. There were no disturbances in EUT functions, so the GMRI robot fulfilled higher quality criteria A, A, A respectively.

3.3. Voltage interruptions – AC power port

Testing voltage interruptions of up to 5 seconds, i.e. 250 cycles, was conducted on the stand featured in Fig. 5 and 6. According to the standard, EUT should fulfil the quality criterion C. Based on the observations of the tested object it was found out that the robot actually fulfils the higher quality criterion B. Temporary worse functioning of the device was related to temporary “freezing” of the camera image and lack of refreshments of measurement results from the sensors of mining atmosphere parameters. After the tests had been completed, the device resumed proper functions.

3.4. Electrical fast transients – AC power port

The tests of electrical fast transients, so called *bursts*, were conducted for the PTSD power supply, transmission and separation device of the robot. During the tests, impulses with pulse rise time 5 ns and duration 50 ns, value of 2 kV, and repetition frequency of 5 kHz were added to the power voltage of 230 V AC. Fig. 7 features a diagram of the stand on which the tests were carried out.

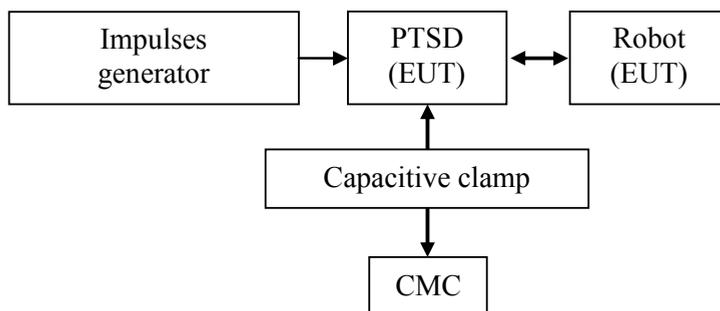


Fig. 7. Simplified diagram for GMRI immunity tests to electrical fast transients on the AC power port

The EN 61326-1 standard permits the quality criterion B which indicates the possibility of temporary worse functioning or temporary loss of the functions, yet the device recovers its proper functions by itself. EUT fulfilled the B criterion. Temporary worse functioning of the device was related to temporary “freezing” of the camera image and the lack of refreshments of measurement results from the sensors of mining atmosphere parameters. After the tests had been completed, the device resumed proper functions.

3.5. Radio-frequency common mode – AC power port

Testing radio-frequency common mode on the AC power port were conducted on the stand featured in Fig. 8. According to the standard, EUT should fulfill the A criterion. During the tests there were no irregularities observed in the operations of the robot (no errors or repetitions in modem transmission, camera worked properly, there were no uncontrolled start-ups of pneumatic electro-valves). The tested device fulfilled the A criterion.

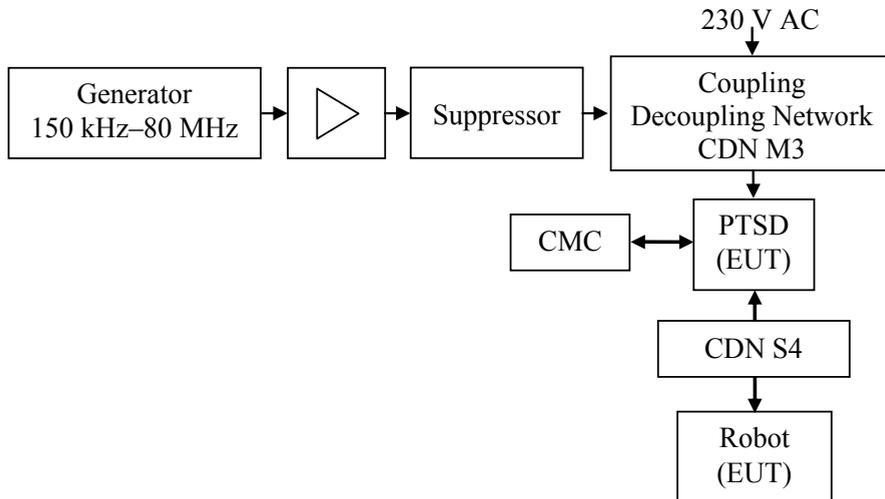


Fig. 8. Diagram for testing GMRI immunity to radio frequency common mode on the AC port (CDN – Coupling Decoupling Network)

3.6. Electrical fast transients – signal port

Testing electrical fast transients, so called *bursts*, on the signal port was conducted on the stand featured in Fig. 9. The tests were based on adding fast 1 kV impulses to the transmission cable between the PTSD device and the mobile robot. According to the standard, EUT should fulfil the B criterion. During the disturbance there was a collapse in the transmission of measurement data from the robot to the CMC console. After the exposure had finished and the cable had been re-connected to the USB socket, in order to check whether the device functions properly, it was found out that the operations of the device were proper. It is important to note that electronic

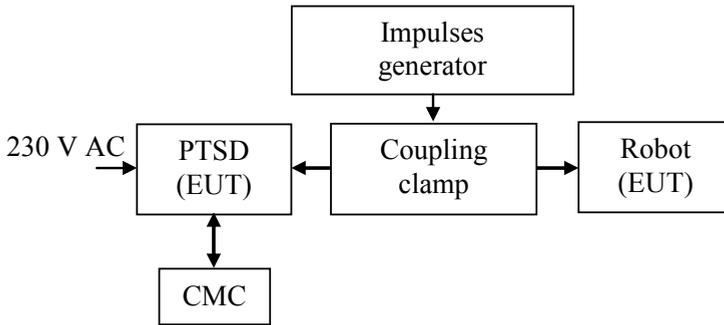


Fig. 9. Diagram for testing GMRI immunity to electrical fast transients on the signal port

subassemblies of the mobile robot worked properly all the time. Thus the tested device fulfilled the B criterion.

3.7. Radio-frequency common mode – signal port

Testing the radio frequency common mode on the signal port was conducted on the stand presented in Fig. 10. According to the standard, EUT should fulfil the A criterion. During the tests there were no irregularities observed in the functioning of the robot circuits. Thus the tested device EUT fulfilled the A criterion.

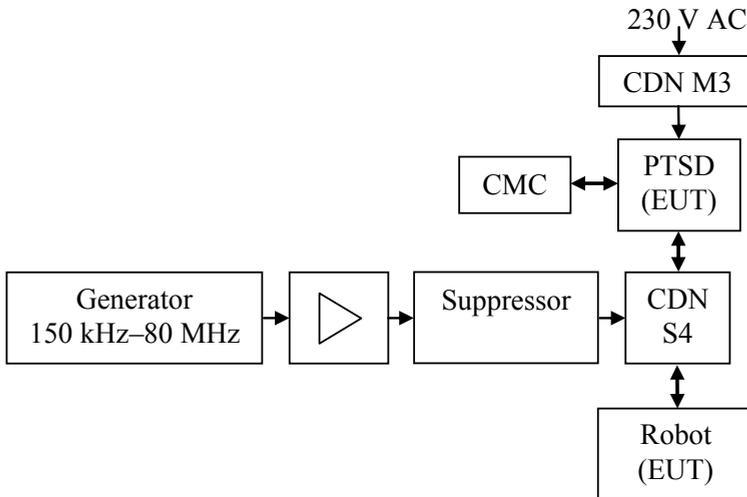


Fig. 10. Diagram of testing GMRI immunity to radio frequency common mode on the signal port (CDN – Coupling Decoupling Network)

4. Emission tests according to EN 61326-1, item 7

Electromagnetic disturbances emission tests were conducted according to the method presented in EN 55011. The measurements of the field emitted by GMRI were conducted in the range from 30 MHz to 1 GHz with a limit level set according to EN 61000-6-4. Figure 11 presents the location of the GMRI robot, along with the PTSD device, in the chamber. During the tests the antenna moves up and down along the mast and changes its polarization (vertical-horizontal). EUT rotates on a rotating table every 90 degrees. More detailed scanning is performed around the measured maximal values. The measurements were done for the robot in two configurations: without connected shields of electrical cables of the robot (Fig. 12) and with connected shields of electrical cables of the robot (Fig. 13).



Fig. 11. Location of GMRI and PTSD in the chamber during the emission measurement

Based on charts from Fig. 12 and 13 it turned out that the robot with grounded shields of electrical cables had worse, yet admissible, emission of an electromagnetic field. Despite these observations, the shields of electrical cables of the robot remained connected due to the fact that the sensors of the mining atmosphere parameters worked properly during GMRI exposure according to section 3.1.

5. Conclusions

Based on electromagnetic compatibility laboratory tests it was found out that the tested device, i.e. the mobile robot and the PTSD stationary system, fulfills its functions.

During the exposure to an electromagnetic field it was found out that the organs of the robot (pneumatic actuators controlled by electro-pneumatic valves) did not perform any uncontrolled moves. The measurement sensors, along with processing and transmission systems, operated in the range admissible by the assessment criteria.

The test results of voltage dips and interruptions proved to be very satisfactory as the tested object fulfilled higher quality criteria than those stipulated by the EN 61326-1 standard.

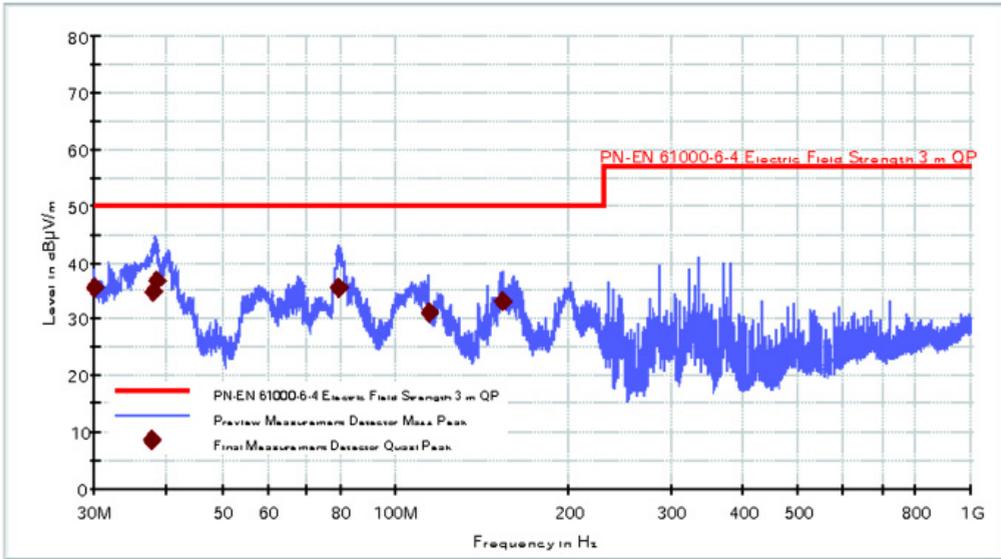


Fig. 12. The chart of GMRI emission without connected shields of electrical cables

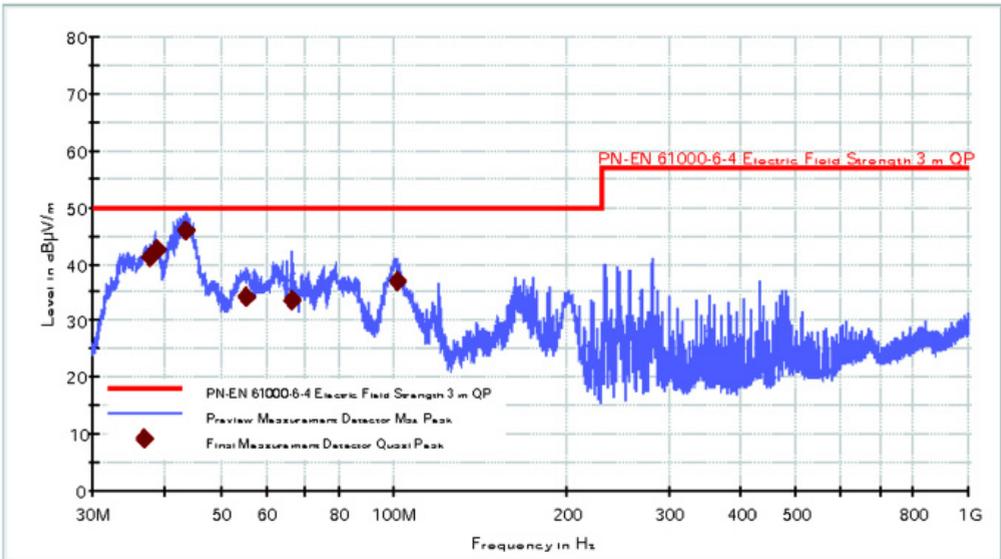


Fig. 13. The chart of GMRI emission with connected shields of electrical cables

The presented testing methodology can serve as a ready-to-use testing algorithm for manufacturers who develop products similar to the described mobile robot for the EU market.

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