THE SURVEILLANCE OF THE INDUSTRIAL ENVIRONMENTS USING ACOUSTIC AND THERMAL INFORMATION SUPPLIED BY A COMPACT MOBILE INTERNET - CONTROLLED ROBOTIC PLATFORM

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This paper presents the integration of acoustic, IR and stereographic assessment technologies within industrial and power plants environments in order to prevent or mitigate emergency situations by using a compact mobile robotic platform. Starting with the Fourth Industrial Revolution, a new demand of modern robotic systems aiming to improve safety and efficiency of modern industrial entities emerged. The main points of interest are control panels, industrial equipment and items that are susceptible to overheating, catching fire and mechanical fault generated noise. The proposed solution integrates a wide range of modern sensorial devices, such as dynamic microphones, LiDAR, stereoscopic and IR cameras that offer a complete and vital set of data that can aid the personnel in conducting efficient and preventive actions.

Keywords: 2D mapping, SLAM, LiDAR, Point-Cloud, stereoscopic camera, image processing, Thermal imaging, Acoustic analysis, Fast Fourier Transform Spectrum

1. Modern industrial safety solutions

The need for modern safety solutions has greatly increased with the integration of Industry 4.0 within all industrial branches. Therefore, modern safety systems integrate a combination of technologies and practices in order to minimize industrial hazards and protect human operators. Sensors, IoT devices, data analytics and machine learning are used to monitor the condition of industrial equipment and infrastructure. For example, operators can conduct preemptive procedures in order to detect hot-spots within industrial electric and control panels or detect premature equipment faults by analyzing the emitted sounds. Furthermore, by integrating

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optoelectronic devices, such as LiDAR module and stereoscopic cameras, can improve detection of surfaces, objects and potential victims in unfavorable conditions, such as smoke [1…5].

As stated, the proposed integrated solution uses a custom designed and manufactured compact and multi-purpose mobile robotic platform as base-frame for the solution. Such mobile robotic platform was developed by the authors of this paper and it is presented in the following Figs. [6].

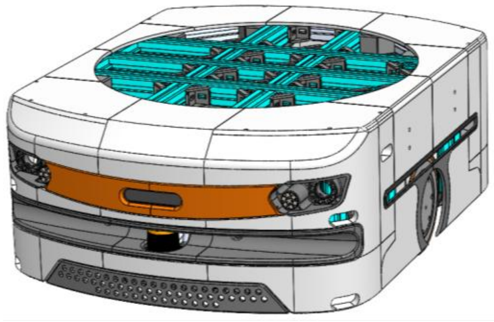

Fig. 1. Mobile robotic platform - CAD view

Fig. 2. Mobile robotic platform front view

1. Real-time acoustic and IR assessment technologies

In order to satisfy a wide range of needs with real-time assessment within specific situations, the mobile robotic platform will be equipped with state-of-the-art electronic equipment. Firstly, the authors propose the integration of a condenser microphone with a cardioid polar pattern. The microphone will capture sounds generated by the industrial equipment, such as manufacture equipment or power machines, in order to detect noise generated by mechanical or electrical defects. Furthermore, the microphone can also be used in order to search for potential victims in case of emergency situations.

Secondly, the authors proposed the integration of a state-of-the-art thermal imaging camera equipped with human and object detection AI algorithms. By doing so, the operators are able to visually inspect machinery and industrial infrastructure in real-time by means of RGB and thermal imaging. In addition to this, the search and rescue operations' efficiency is enhanced by the camera's on-board customizable AI algorithms used for human and object detection. More, the authors integrated of a LiDAR module and a stereoscopic camera used for bidimensional and point-cloud based volumetric assessment. The LiDAR module and stereoscopic camera can be integrated within the mobile robotic platform and the microphone and thermal imaging camera can be mounted on top of the mobile robotic platform by using a custom-made aluminum interface.

2.1 Real-time acoustic assessment

The use of a microphone within industrial environments is very useful in detecting sound-based equipment anomalies and potential human victims. Next, the used microphone is a *Streamplify* condenser microphone dedicated to capturing sound waves with high fidelity by having a cardioid sensitivity pattern. Therefore, the microphone has the highest sensitivity to sound coming in directly in front of the microphone, reduced sensitivity from the sides and close to zero sensitivity coming from behind. This feature is extremely useful in order to isolate unwanted sounds coming directly from the behind of the microphone and enhancing the audio capturing process. The used microphone, main technical specifications and pickup pattern are presented next:

Fig. 3. The Streamplify microphone used during testing and integrated within the platform

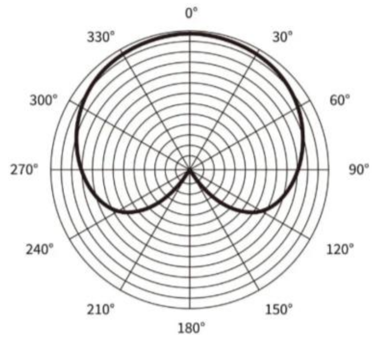

Fig. 4. Cardioid pickup pattern of the Streamplify microphone [7]

The main specifications are the following: Sensor type: Ø16mm condenser capsules; Number of condensers: 1; Pick-up pattern: cardioid; Sampling rate: 16bit, 48kHz; Frequency response: 100Hz - 18khz; Singal to noise ratio: >85dB; Sensitivity: <-36dB±3dB; Sound pressure level: 120dB; Impedance: <680Ω.

Integration of the microphone with the mobile robotic platform is made by using the dedicated foldable arm, mount shock mounted on the aluminum frame interface. Several tests have been conducted with the microphone by capturing sounds produced by various industrial related equipment. For testing purposes, an air compressor and a server room were recorded in order to perform an acoustic analysis aiming to determine peaks and the related frequency in the sound waves produced by the tested equipment. For this test, the microphone is connected via USB cable to the Ubuntu-equipped onboard computer. Once the microphone is pointed to the subject of the acoustic analysis, the spectrums of the produced sound can be visualized by using the Friture application. Three spectrums can be visualized in real-time, such as 2D Spectrogram, Fast Fourier Transform Spectrum and Octave Spectrum.

2.2 Real-time thermal imaging assessment

The use of thermal imaging camera within industrial environments is paramount in order to prevent disasters, including fires, expensive equipment damages and human victims. Therefore, the authors implemented a state-of-the-art camera with RGB thermal imaging and AI detection algorithms capabilities. The chosen camera is a Viewpro A40T Pro due to its excellent imaging capabilities (Fig. 5). Next, the technical specifications of camera are presented [7, 8]:

Fig. 5. Viewpro A40T Pro [8]

- RGB image sensor: $1/2.8"$ Sony CMOS Sensor;
- RGB resolution: 1920x1080 ;
- Optical zoom: $40x$;
- Digital zoom: $2x - 32x$;
- IR Thermal imager focal length: $19\ mm$
- IR Thermal imager resolution: 640×512
- IR color palette: white hot, black hot, pseudo color.

The presented camera is mounted of the mobile robotic platform by using the custom-made aluminum frame interface. The IR capabilities of the A40T Pro consist of three selectable color palettes, such as *Ironbow*, *White-hot, Black-hot¸* and also various *Picture-in-Picture* displaying modes in combination with RGB video feed.

2.3 Integration of acoustic and IR assessment technologies

Authors of this paper have integrated the presented acoustic and thermal imaging technologies within the mobile robotic platform in order to be able to perform a wide range of acoustic and visual analysis based on the data captured. The acoustic and IR assemblies are presented in the Figs. 6…9.

Fig. 6. Acoustic assembly

Fig. 7. Acoustic assembly with extended arm

Moreover, the mobile robotic platform is equipped with a portable screen used for real-time data observing and debugging. The complete and integrated system is presented in the Figs. 10 and 11.

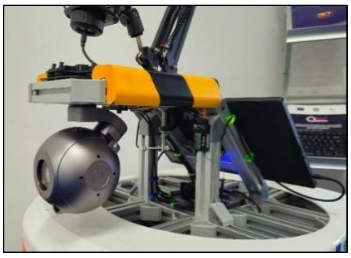

Fig. 8. IR Camera assembly

Fig. 9. On-board screen

Fig. 10. Acoustic and IR integrated solution

Fig. 11.Front view of integrated solution

2.4 Experimental validation of the integrated acoustic and IR solution

In order to test the functionality of the solution as a whole, the authors performed an acoustic and IR analysis for a server-room. The aim of the analysis is the determine peaks and the related frequency in the sound wave produced by the tested equipment. The microphone is connected via USB cable to the Ubuntu-equipped onboard computer. Once the microphone is pointed to the subject of the acoustic analysis, the spectrums of the produced sound can be visualized by using Friture. The aim of the IR imaging is to detect abnormal equipment hot-spots in order to predict and prevent failures. For this test, the IR camera is connected via Ethernet to the onboard computer. The resulted images are streamed via a dedicated network-stream. The test scenario is presented in Fig. 15, where the mobile robotic platform is positioned in front of the server rack with the microphone arm extended towards. The real-time measurements regarding acoustic and IR analysis are displayed on the on-board screen.

Regarding the acoustic analysis, a measurement was performed prior to starting the servers and after. The result provided by *Friture* for the both testing stages is presented in the Figs. 12…16 by comparing the FFT (Fast Fourier Transform), Octave spectrums and 2D Spectrograms.

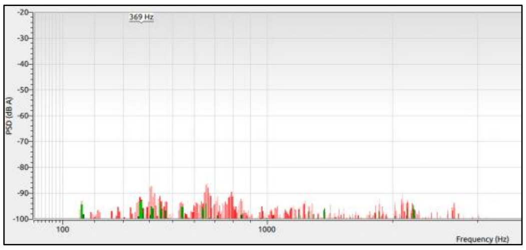

Fig. 12. FFT Spectrum – pre-start-up

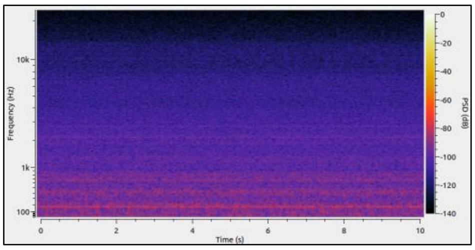

Fig. 13. 2D Spectrogram - pre-start-up

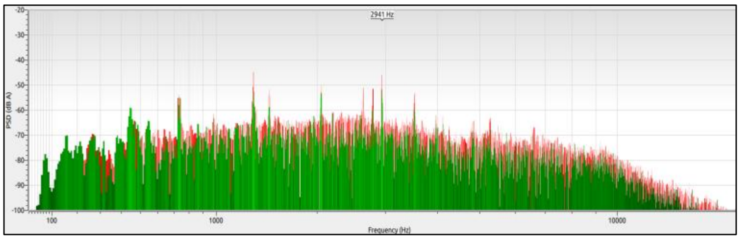

Fig. 14.FFT Spectrum – post-start-up

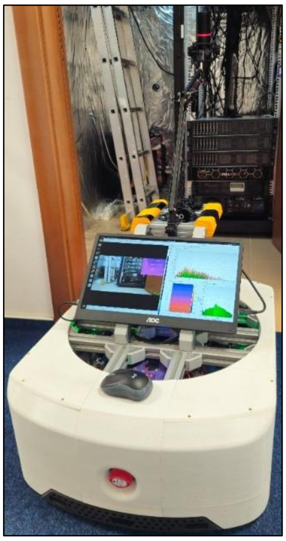
Fig. 15. Image taken during acoustic and IR testing

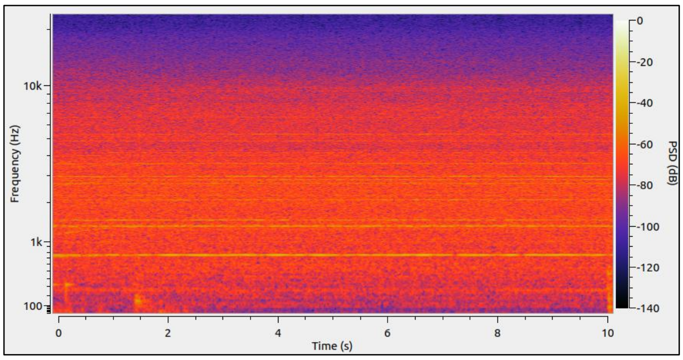

Fig. 16. 2D Spectrogram post-start-up

From the figure above it is shown that the peak frequency generated by the servers while functioning is about 2.941Hz. Regarding the Octave Spectrum, the comparative analysis is presented in the Figs. 17 and 18. Based on the Figures above, the frequency spectrum generated by the servers is focused in the mid and high-frequency domain.

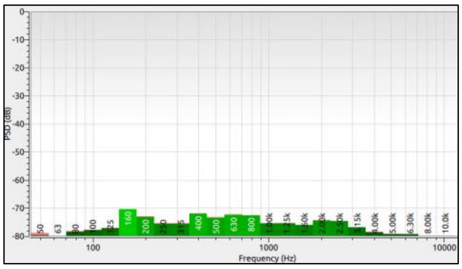
Fig. 17. Octave Spectrum – pre-start-up

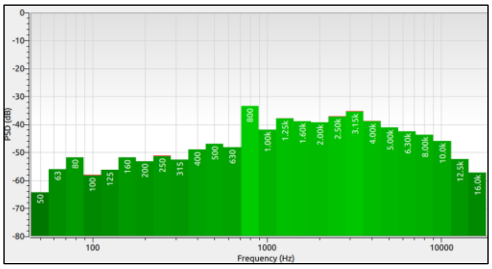
Fig. 18. Octave Spectrum – post-start-up

Regarding the IR imaging analysis, the thermal camera is pointed to a server rack in order to detect any hot-spots. The live-view provided by the IR camera is presented in Fig. 19.

Fig. 19. Thermal image of the server rack

In the image above a few servers-related hot-spots are found on the servers' power supply front cover. These are generated by the cooling fan and the digital display of the power supply. Furthermore, the IR imaging can also be used for detecting individuals within search and rescue operations, where the visibility is very poor, e.g., smoke, loss of lights [9, 10]. In the next four Figs. (20…23), the camera is tested by pointing it to one of the authors:

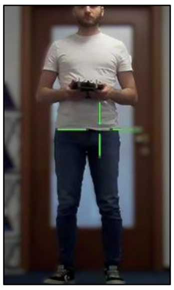

Fig. 20. RGB image

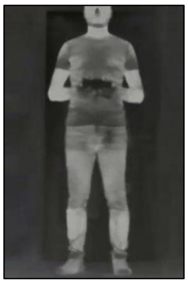

Fig. 21. IR Thermal imaging - White-hot color palette

Fig. 22. IR thermal imaging - Black-hot color palette

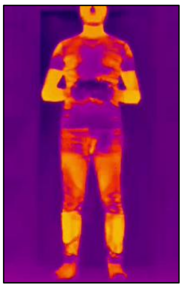

Fig. 23. IR thermal imaging – Ironbow color palette

The authors also tested the thermal capturing capacities in an **industrial environment**, in a manufacturing company specialized in mechanical components manufacturing for automotive and aerospace industry, and also components for control vanes and piping. Using the thermal solution presented above, authors captured RGB and thermal images of a range of relevant equipment within the presented industrial environment, such as various photovoltaic inverters. In the next figures, the results are presented as follows:

Fig. 24. Victron Energy inverters – RGB image

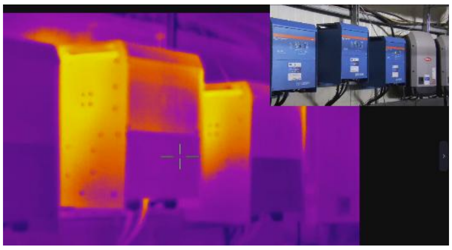

Fig. 25. Thermal image of the inverters

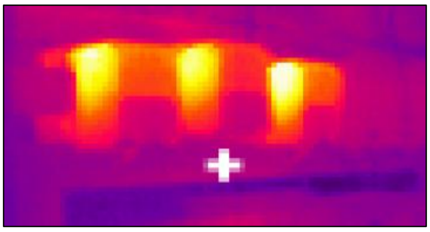

Fig. 26. Thermal image captured by handheld FLUKE Thermal

Fig. 27. Deye inverters – RGB image

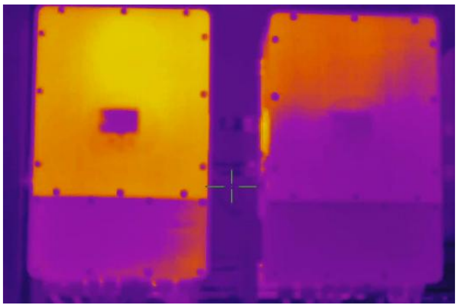

Fig. 28. Thermal image of the inverts

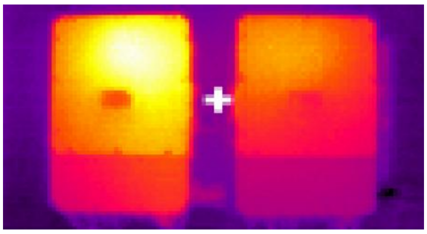

Fig. 29. Thermal image captured by handheld FLUKE Thermal

The images above are captured using the proposed solution with the integrated **Viewpro A40T Pro** RGB – IR imaging camera, Figs 24, 25, 27, 28 and with **FLUKE 279 FC** True RMS thermal multimeter, Figs. 26, 29. This was performed in order to validate the functionality of the onboard RGB-IR camera, **Viewpro A40T Pro**. By conducting the presented IR capturing tests, the thermal imaging report states that the **Victron Energy inverters** reached a maximum recorded temperature at $t_{max1} = 39.6°C$, and the **Deye inverters** reached a maximum recorded temperature at $t_{max2} = 36°C$.

During testing, a hot spot was detected within the power lines' rail between the Victron Energy inverters was. The hot spot is presented in Fig. 31.

Fig. 30. Power lines rail

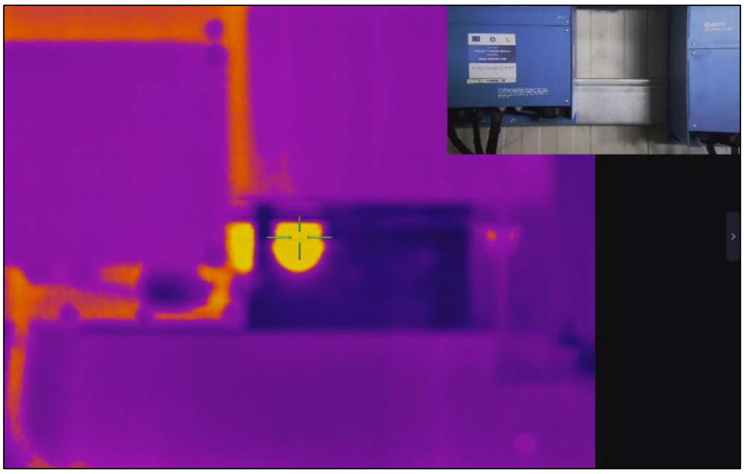

Fig. 31. Hot-spot detected

The tests conducted within the presented industrial environment proved to be accurate and successful, thus offering valuable information regarding performance of working state of equipment.

3. Integrated real-time 2D and 3D laser-based technology assessment

In the context of mapping the industrial environment, laser technology is best suited due to excellent accuracy and repeatability. By implement such devices within the structure of a mobile robotic platform, operators are able to create 2D and 3D maps of the industrial environment with centimeter-grade fidelity. Furthermore, due to the depth-vision capabilities provided by the stereoscopic camera, operators are able to detect and distinguish objects and human victims in no-light and/or smoke-filled environments, helping the intervention teams in related scenarios. The authors of this paper have integrated the mentioned devices withing the structure of the designed robotic platform by stacking the LiDAR module and stereoscopic camera in top of each other in the front section of the robotic platform as follows in Fig. 32.

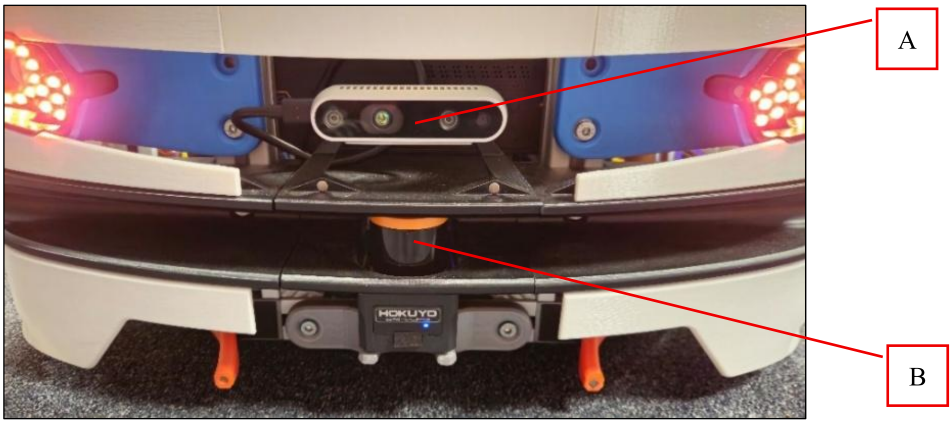

Fig. 32. LiDAR and stereoscopic camera: A – Intel D435i; B – HOKUYO UST-10LX

By choosing this integration method, the 3D point-cloud output of the stereoscopic camera can be overlapped on the 2D plane constructed by the LiDAR module. By doing so, operators receive more accurate results concerning the state of the industrial environment.

a. Bidimensional area assessment

In order to accurately generate bidimensional maps of the designated industrial environment, a powerful and precise laser-based measurement device is required [11…17]. To do so, authors of this paper have chosen an industrial-grade LiDAR, the Hokuyo UST-10LX, Fig. 33, an acclaimed LiDAR module used for various application, including mobile robotic platforms intended for industrial use. The main technical specifications are the following: range: 10m; field of view: 270º; scan frequency: 40Hz; protection class: IP68; accuracy: ±40mm; angular resolution: 0,25º.

Fig. 33. HOKUYO UST-10LX LiDAR

Furthermore, the LiDAR module is connected via Ethernet protocol to the mobile platform's integrated computer. The data provided by the LiDAR can be accessed using the ROS2 visualizer application, Rviz, as follows.

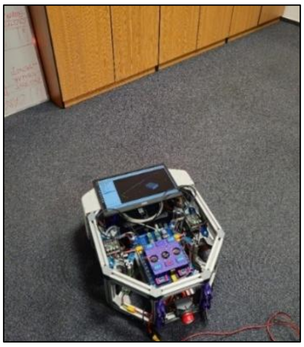

Fig. 34. LiDAR data acquisition system

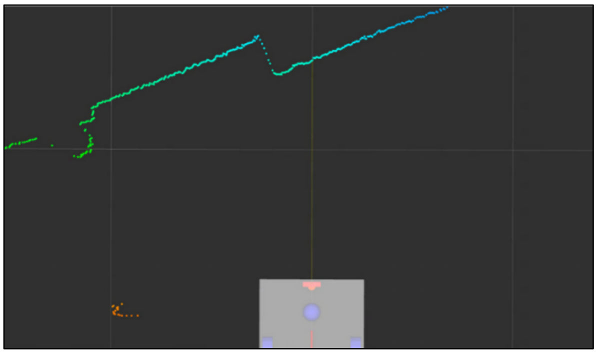

Fig. 35. RViz view – LiDAR wall detection (top view)

Next, the bidimensional map can be generated using Rviz application. The results are presented in Figs. 35…39. The mapping procedure consists of gathering data starting from the starting position and advancing throughout the floor with constant speed in order to accurately create the map of the floor.

Fig. 36. 2D floor mapping procedure – starting position

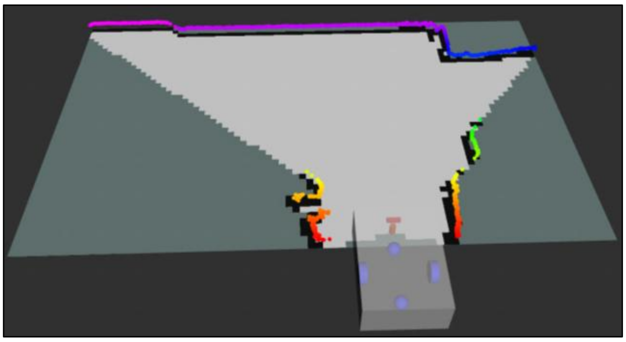

Fig. 37. 2D floor mapping starting procedure (RViz view)

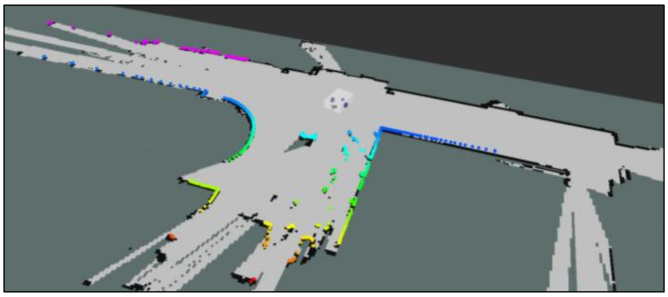

Fig. 38. 2D floor mapping procedure - intermediary stage - lobby

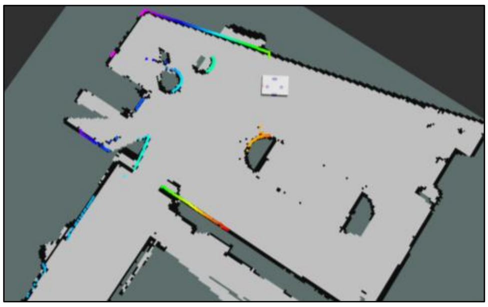

Fig. 39 - 2D mapping procedure - intermediary stage – meeting room

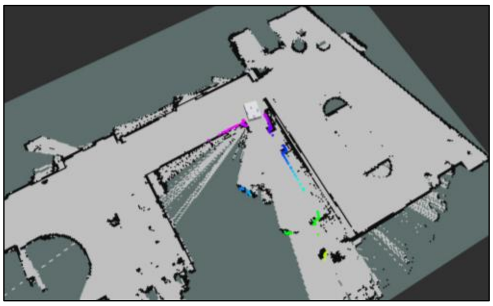

Fig. 40. 2D mapping procedure - final stage

After the mapping process is complete, the operator is able to export the entire map in various formats using the Rviz's integrated map exporter. For example, the image from Fig. 41 represents the map in a *.jpg* format.

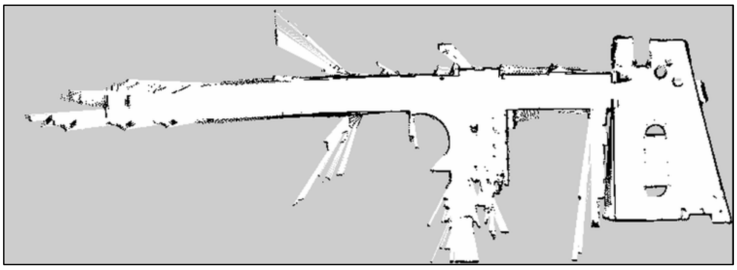

Fig. 41. Exported 2D map

b. Point-cloud based volumetric assessment

Using the point-cloud based volumetric assessment, operators are able to identify volumes or even human individuals within dark or smoke-filled rooms or areas. This capability is very valuable in an emergency situation where emergency teams are conducting search and rescue operations. Therefore, the authors have chosen the stereoscopic camera, Intel D435i, due to the small form factor and high performance considering the small form factor.

Fig. 42. INTEL RealSense D435i

Specifications of this device are the following: range: 0.2-10m; depth resolution: up to 1289x720; RGB resolution: up to 1920x1080; field of view: 90º; integrated 6DOF IMU. Next, the stereoscopic camera is connected to on-board computer via USB. By initializing the RGB and point-cloud stream, the results can be accessed using the ROS2 visualizer application, Rviz, as in the Figs. 43, 42 and 45.

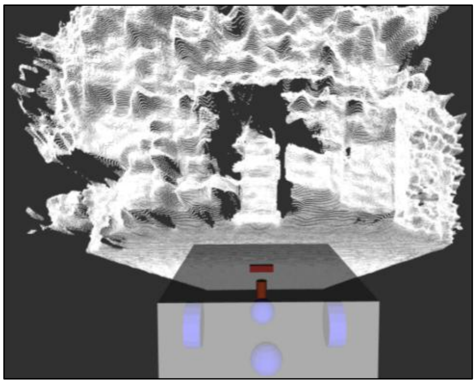

Fig. 43. Rviz Point-cloud results – 3D robotic platform's 3rd person view

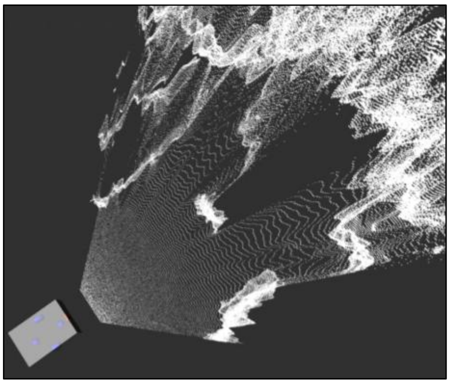

Fig. 44. Rviz Point-cloud results – 3D top-down view

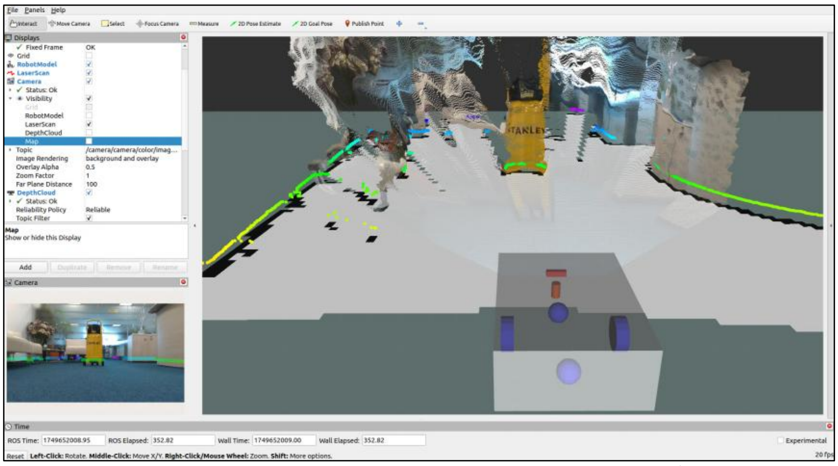

Fig. 45. Rviz RGB point-cloud results - Robotic platform's 3rd person view

In the figures above, the real-time point-cloud information is presented with the aid of *RViz.* In order to validate the volumetric perception of the stereoscopic camera, an air compressor is placed in front of the robotic platform. The air compressor can be observed in the bottom left corner of the figures above, where the RGB live feed of the stereoscopic camera is set. In Fig. 44, a top-down view of the point-cloud is presented, where the "shadow" of the air compressor can be distinguished, proving the depth perception capability.

4. Conclusions

The main target of this paper was the integration and experimental validation of modern industrial environment assessment and *search&rescue* technologies and equipment by using a custom designed and manufactured, multi-purpose, retrofittable and compact robotic platform. The equipment and technologies implemented are: RGB-IR camera, RGB-Depth perception camera, industrial-grade LiDAR and condenser-cardioid high-sensitivity microphone.

In most of the predictive maintenance situations, operators search for unusual behavior of equipment, such as abnormal sounds and unusual temperatures that may occur during functioning. With the aid of sound capture equipment and real-time acoustic analysis operators are able to detect hydraulic fluid leaks, frictions, or mechanical failures. In addition to this, the IR thermal imaging provides real-time thermal information in *Ironbow*, *White-hot* and *Black-hot* color palette regarding human detection and industrial equipment, such as steam turbines, hydraulic machinery, control and electrical panels, photovoltaic panels and inverters, powerlines and so on. By combining the real-time acoustic and thermal analysis, operators are able to perform predictive maintenance procedures much more efficiently, thus minimizing equipment's down-times, repair costs and failure chance. The LiDAR and stereoscopic camera are very useful in providing real-time planar and volumetric information of the industrial environment. Therefore, bidimensional maps can be created with centimeter precision no matter the light conditions.

By integrating the on-board LiDAR and stereoscopic camera with the acoustic and thermal analysis technologies, the authors succeeded integrating real-time assessment technologies within a compact robotic platform with the general aim of preventing industrial disasters and human casualties, thus providing a safer and more efficient industrial environment within automotive, aerospace, manufacturing and energy industries. In addition to this, the authors conducted field tests within an industrial environment, a automotive, aerospace and miscellaneous components manufacturing entity, with the goal of visually inspecting working and relevant equipment for this paper, such as various photovoltaic inverters and power lines.

Acknowledgement

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SMIS No. 121220, Contract No. 255/ 05.06.2020. The platform is currently used for thermal and noise investigations in the hydropower plants running on the Olt River cascade, surveying the leakages of fluids, and the hot spots in electrical panels of an aerospace manufacturing company.

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