# Hardware/Software Solutions For an Efficient Thermal Scanning Mobile Robot

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**Abstract –**

**The use of robotic platforms greatly facilitates the reconstructions of 3D models of buildings and automates tasks that would be tiring and inaccurate when carried out manually. In the specific area of thermal monitoring of buildings, robots can also develop an important role providing dense temperature information of envelopes and structural elements. However, the current robot-based systems that extract thermal models can work under serious restrictions that concern, among others, the complexity of the scene, autonomy, navigation, and computation. This article discusses the limitations and restrictions of the current mobile scanning robots for thermal mapping inside buildings and proposes a thermal scanning robot that solves some of these issues.**

**Keywords –**

**Robotic platforms; Thermal scanning; Thermal point clouds; FoV; Building sensoring**

## 1 Introduction

The use of robots and UAVs are being expanded in the AEC industry in recent years. Particularly, when it comes to the acquisition of geometry and characteristics of buildings, such automatic systems allow to reduce the time required for on-site work, as well as to improve the accuracy of the collected data. In the case of thermal digitization, the arrival of 3D thermal scanning systems is giving a new dimension to the thermal analysis of buildings as they provide larger amount of information than those that only work with 2D infrared cameras, thus showing a complete thermal representation of a building. In essence, the robot must capture points and temperature of the scene to generate a thermal point cloud (TPC) that can be later processed.

Although the thermal scanning platforms are evolving day-to-day with new functionalities in larger and complex environments, there are still many restrictions and limitations that must be overtaken in the next future. A comparison of the main mobile thermal cloud acquisition platforms, including our systems, can be seen in [1] and [2]. In the next section, the most important limitations and issues regarding both hardware and software of the current thermal scanning platforms (TSPs) are described.

## 2 Limitations of the current thermal scanning platforms

In this section Hardware and Software limitations will be dealt with separately.

### 2.1 Hardware limitations (HL)

In the case of TSPs, the term "hardware" refers to the physical devices of the system, such as the robot base and sensors. There are several limitations in this matter that are still poorly addressed in the existing literature, which could be summarized as follows.

- HL1. Autonomy. Refers to whether the robotic platform navigates by itself, as in Adán et al. [3] and Borrmann et al. [4], or is commanded by a specialist technician, as the system presented by Hoegner et al. [5]. Besides, the possibility of carrying out a multi-session data campaign at different positions of the building, or at different times, also refers to an autonomy issue. Usually, an operator turns the system on and off at the appropriate times in case of multi-session processes. Most systems are therefore considered as semi-automatic.
- HL2. Scene. Refers to the characteristics of the scenario and their surroundings in which the platform navigates. We can differentiate between terrestrial TSP ([6], [7]) and UAV [8] systems. In the case of terrestrial platforms, some usual restrictions are flat floors with no stairs/steps and no multiple floor levels. In addition, there are also evident navigation problems in furnished indoors with few and small free spaces. For UAVs, there are also limitations when working in narrow spaces. Most of the current TSPs move

on wide spaces and unoccupied buildings, which signifies a serious restriction with respect to the type of scenes.

- HL3. Limited FoV. The reduction of the field of view in thermal cameras is an issue that has been discussed previously (Previtali et al. [9] or in Alba et al. [10]). The limited FoV of TIR makes the thermal point cloud be incomplete as it only assigns temperature to a part of the point cloud. Few TSPs have addressed and solved this issue.
- HL4. Batteries. All TSPs have power consumption restrictions on each one of their components. Usually, consumption is supported by batteries paired to one or more elements that make up the platform, so there is a restriction on the time of use depending on these power supplies. As a consequence of this, long data sessions and large scenarios should be avoided with poor power resources.
- HL5. Weight and dimensions. Heavy or large platforms are difficult to move from the lab to the environments where digitization is performed. Additionally, big platforms also make difficult to navigate in narrow environments or in passages between rooms, as in the case of the platform presented by Adán et al. in [3]. Other heavy platforms are on board of vehicles that navigate in outdoors of urban environments, such as the one of Hoegner and Stilla [11]. This limitation makes impossible to obtain thermal model of usual apartments and houses.
- HL.6. Costs. The cost of a robotic platform is usually high, especially when considering an expensive terrestrial robot base and/or a sophisticated 3D sensor as a scanner. This is usually the case of UAVs, as it was previously addressed by Bulatov et al. [12] and Sun and Zhang in [13], or when using LIDAR technology, as in the system by Borrmann et al. [4]. Few low-cost TSPs can be found in literature.

## 2.2 Software limitations

Software limitations refer to the programming of the robot, as well as problems related to data transfer between different parts of the system or data storing.

- SL1. Robot programming. The bibliography shows that most of the robots used in the AEC industry are programmed under the Robotic Operating System framework (ROS), which can be limiting as it requires programmers and technicians specialized in this framework for its operation. ROS works under Linux operating system, while its operation with Windows is still under development today. This is also a limitation in case of looking for interoperability between different systems and OSs. Kim and Peavy [14] show a retrieving method of building data using robots under this programming. Kyjanek et al. [15] describe a custom robot platform with ROS path planning for the human-robot collaboration in timber prefabrication. Meschini et al. [16] present a novel methodology on how to link ROS with a BIM model for automation in construction.
- SL2. Sensor programming. External sensors on board the robot base, such as cameras or scanners, must be programmed and integrated in ROS using compatible drivers. Additionally, it is very common to use a Software Development Kit (SDK) for each sensor. Therefore, specific programming tools for sensors are required.
- SL3. Multisession programming. There is hardly any bibliography that addresses performing multi-session data collection with robotic platforms, either performing data collection in the same place or using different sessions at different locations to obtain better coverage of the architectural space or thermal characteristics. Exceptions can be found in [17] and [18]. In Adán et al. [17] the system scans a wall in evenly spaced intervals of time to test its temperature evolution. In Rakha et al. [18] a drone is used to take 2D TIR pictures of the exteriors of a building during a determined period of time.
- SL4. Use of memory. For acquisition systems dealing with millions of points, there may be memory problems if the external storage system is not properly sized. In Xiong et al. [19] this problem is addressed by sub-sampling each scan. In López et al. [20] a sparse matrix instead of a fixed size matrix is used to represent a depth buffer in an optimized approach for thermal point clouds using an UAV platform.
- SL5. User interface. This is related to the framework used to manage a TSP, thus defining the proper planning and tracking the evolution of the data acquisition session . The use of efficient user interfaces in the AEC industry is essential. This facilitates the use of the TSP in multidisciplinary teams without experience in computer programming. None of the aforementioned papers presents a user interface to be used by construction workers.

# 3 MoPAD2: a reliable thermal scanning robot

In this section, a new thermal scanning platform is presented. MoPAD2 (Mobile Platform for Autonomous

Digitization) features some solutions for the earlier limitations and drawbacks. MoPAD2 is shown in Figure 1. MoPAD2 is a new platform that is a considerable improvement to the former version in terms of data collection, management, scope, and processing. For each item discussed, the contribution of MoPAD2 to limitations HL1-HL6 and SL1-SL5 will be pointed out in brackets.

### 3.1 Hardware solutions

- Robotic base (HL5, HL6, SL1). MoPAD2 is built on a TurtleBot 2 robot kit with a low cost and reduced size Kobuki robot base. This nonholonomic mobile robot can carry up to 5 kg and it is implemented in ROS.

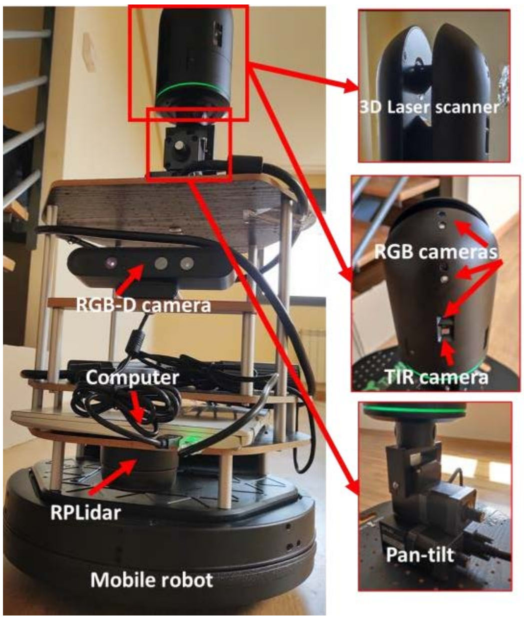



Figure 1. MoPAD2.

- Robot autonomous charging (HL1, HL4). The TurtleBot 2 includes a docking station (see Figure 2) that allows autonomous charging. Thus, multiple sessions can be carried out without human intervention. An example of autonomous charging can be seen in Section 4.

Figure 2. Docking station.

- 3D scanner (HL4, HL5, HL6). In our autonomous platform point clouds are captured using a mid-range 3D laser scanner (Leica BLK360). This small and lightweight scanner has a minimum range of 0.6 meters and a maximum range of 60 meters. Its field of view of 360º x 300º (h x v) covers practically the entire visible space. It has three integrated RGB cameras that rotate with the scanner, capturing 30 images in one complete turn. The entire space is covered by the 15Mpx panoramic image obtained.
  The scanner is powered by a removable battery, which enables 3 hours of continuous use. In order to extend the autonomy of the 3D scanner an external switch actuator is integrated.
- Thermal camera (HL3). The scanner also has an embedded thermal camera (FLIR IR camera) with a resolution of 160 x 120 pixels and a field of view of 71° x 56° (v x h). It can work in a temperature range from -10 °C to 65 °C, and has a thermal sensitivity of 0.05 °C. This camera obtains 10 overlapped thermal images as it rotates with the scanner. Thus, a panoramic image with a 71º vertical field of view can be generated. In order to solve this reduced FoV, a pan-tilt platform is integrated into MoPAD2.
- Pan-tilt platform. (HL3). The pan-tilt unit shown in Figure 3 (FLIR PTU E46) is incorporated to solve the lack of vertical range of the thermal camera. The FoV is increased by tilting the scanner. Pan movement is not used as the scanner rotates itself. As a consequence of this, an omnidirectional thermal image of the scene can be generated.

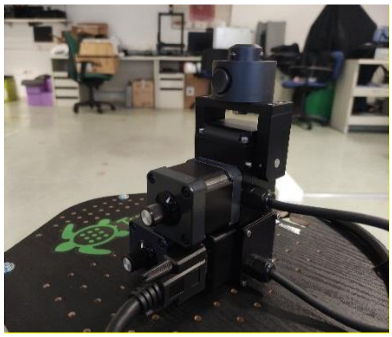


Figure 3. Pan-tilt platform.

- Switch actuator. (HL4, SL3) As a power saving measure, the 3D scanner needs to be switched off during idle periods, such as waiting time between sessions. For this reason, a switch actuator (see Figure 4) has been developed. This actuates the scanner button. This way, the power usage issue is optimized, which increases the autonomy of the 3D scanner in case of a multi-session campaign.

Figure 4. Switch actuator.

- Computation and memory (SL4). MoPAD2 is controlled by a computer at 4.7 GHz. There is an external computer used by the operator to control the robot and define scanning sessions. It is also used as a data server in which point clouds and thermal images are stored to release memory from the computer in MoPAD2.
- Sensors for navigation (HL2). There are two sensors on board MoPAD2 that have been used depending on the type of the scenario. For textured and inhabited environments, the Orbbec Astra RGBD camera, with a range of 8 meters and a resolution of 1280 x 960, provides an efficient SLAM. The second sensor is the Slamtec RPLidar A2M8 laser rangefinder with a range of 6 meters. This is used in non-textured and uninhabited interiors. Therefore, robot location and navigation issues are efficiently covered for a variety of textured and non-textured environments.

### 3.2 Software solutions

- ROS integration. (SL1). All MoPAD2 components except the scanner and the switch actuator are implemented in ROS. The algorithms and functions are ROS-based as well. Even though ROS is a limiting factor for non-expert personal, this problem is solved with the addition of a user-friendly interface.
- Sensors and actuators programming. (SL2). The laser scanner and the TIR camera have been programmed using their own SDKs, which allows to customize data acquisition parameters. The switch actuator is controlled by a script running on a Raspberry Pi Pico microcontroller.
- Communication and data transference. (SL1). The different components of the system are connected via Wi-Fi. There are two networks: scanner network, which communicates the scanner with the robot; and MoPAD2 network, which communicates the robot with the switch actuator and the control server. The communication and data transference are represented in the diagram in Figure 5. As all the acquisition and navigation processes are embedded in the robot computer, server connection is not required during data acquisition.

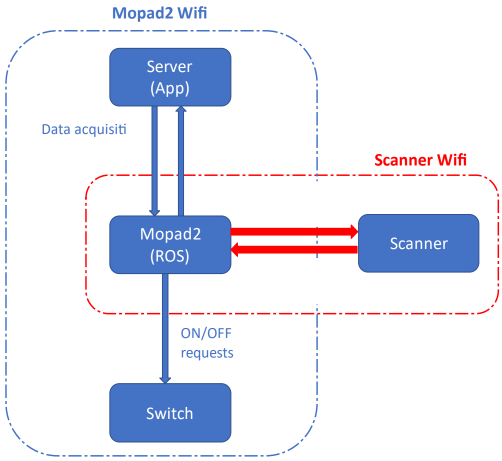



Figure 5. Communication and data transference.

- Multi-session programming. (SL3, SL4). Figure 6 shows the general scheme of a multi-session campaign.[A1] There is an offline phase (1) in which the scene's map is obtained. This map can be used in subsequent sessions if the scenario does not vary. At the session definition (2), some parameters are defined by the user such as: number of sessions, time between sessions, robot poses and scanning parameters. Data acquisition (3) for every defined session is then conducted. The robot navigates towards each previously stop point, where data is collected as planned beforehand. Data acquisition ends when the platform docks at the charging station. At this moment, point clouds and thermal images are sent to the server. Data is then deleted from memory in the robot and stored in a hierarchic database, which is structured in levels: day, session, zone, and position.
In the data processing stage (4), various registration algorithms are carried out in order to obtain an omnidirectional thermal point cloud of the scenario ([21]). The point cloud registration problem is primarily solved by employing the localization data obtained from the mobile robot, and is later refined by applying the well-known ICP (Iterative Closest Point) technique ([22])

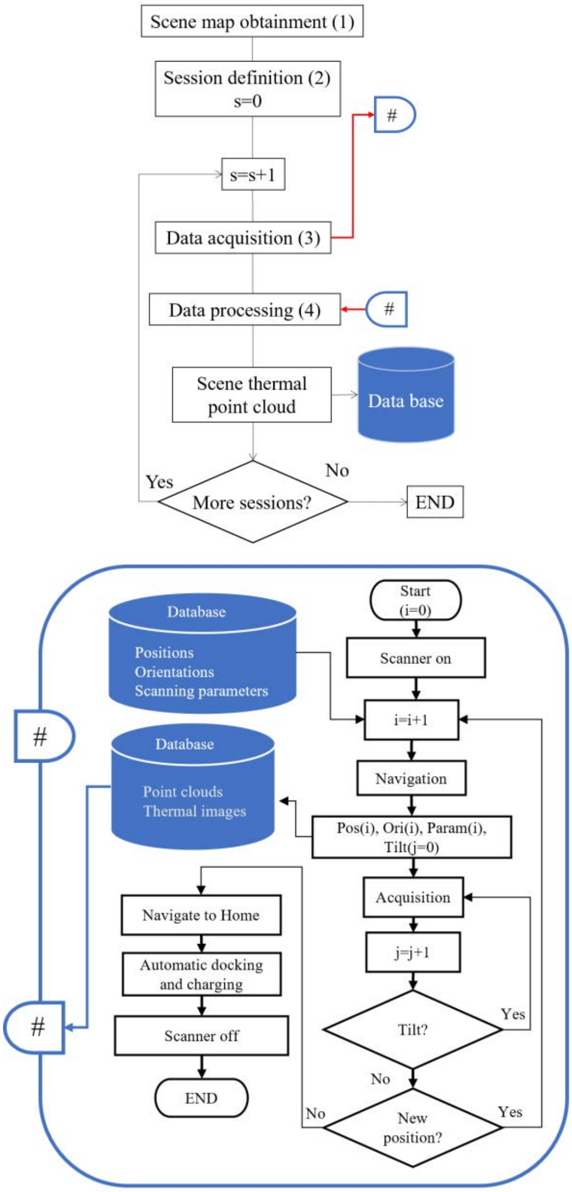



Figure 6. General scheme of a multi-session campaign.

- App. (SL5). MoPAD2 app has been developed to manage and control the robot during the data acquisition sessions (see Figure 7). Its interface includes an image of the scenario map with the current robot position and a set of buttons with different functionalities. Among others, the user can define the number of sessions, the time intervals between them, the type of data and specific the stop positions from which MoPAD2 will scan the scene. Moreover, the user can initialize components and manually command the robot. This app is therefore ready to be used by non-expert construction personal.

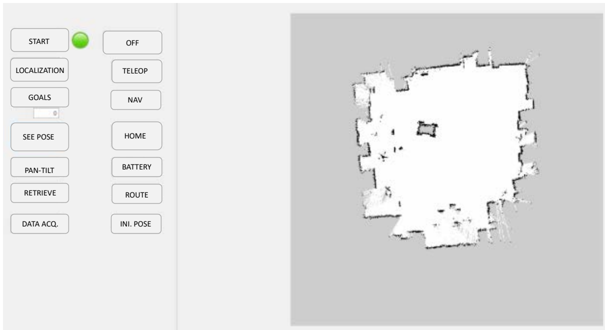



Figure 7. Interface of MoPAD2 control app.

## 4 Testing MoPAD2

MoPAD has successfully been tested for thermal digitization of interiors of buildings at floor scope, but there are some issues and restrictions that should be addressed in the future. First, the cost of MoPAD2 is still high and some of the sensors could be replaced or substituted by others, thus simplifying the whole platform. For example, the pan-tilt platform could be removed if a second thermal camera is coupled to the scanner set. In this way, the FoV issue would be solved. Second, the system which powers the scanner must be replaced if we want to tackle longer and larger-in-time single scanning sessions and, of course, larger multi-scanning sessions. Third, although the current MoPAD2's app is ready to be used by a multidisciplinary team, improvements in visualization and functionality aspects must be conducted.

Other limitations will remain in MoPAD2 without solution. These are: navigation in flat floors without stairs or steps and the still limited power supply capacity.

In this section, two experiments in different scenarios are presented.

The first experiment (see Figure 8) has been carried out in a part of an uninhabited conventional building with Manhattan structure. This scenario is composed of 4 rooms connected by doors. It has an area of 187 $m^2$ and a volume of 748 $m^3$ (see Figure 9).

A total of 180 thermal images and 18 scans at 6 positions of the robot were needed for the thermal digitization. The omnidirectional thermal point cloud of the whole scene contains 88 million points. Two sessions were conducted on the same day with an interval of 5 hours (9 a.m. to 14 p.m.). Figure 10 shows the thermal point cloud of Zone 1 in both sessions using a colour palette range of [25ºC, 35ºC]. It is worth noting the evident increasing of the temperature (although with different degree) in walls, ceiling and floor in the second session.

a) b)

Figure 8. a) MoPAD2 in scenario 1. b) MoPAD2 docking in charging station.

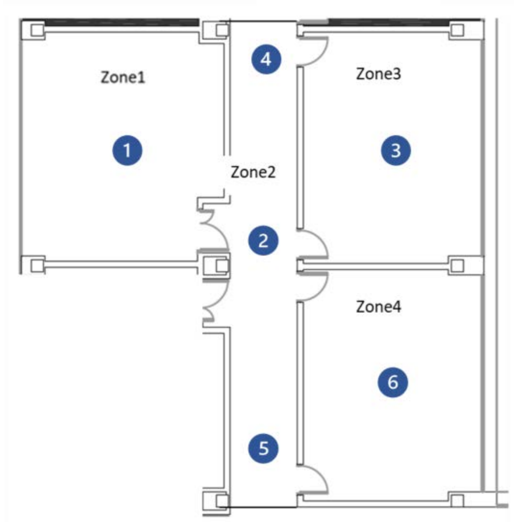
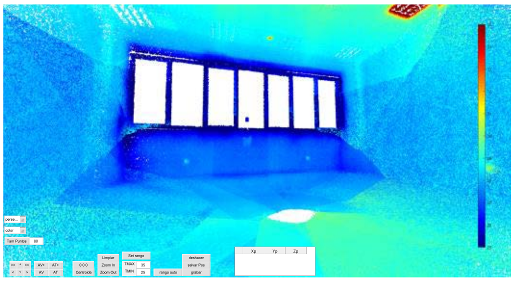



Figure 9. Floor plan of scenario 1 and stop locations in which the thermal scans have been taken.[A2]

The second validation test (see Figure 11) was carried out in an uninhabited apartment about 70 square metres, composed of 4 large rooms, 2 small rooms and a narrow corridor connecting them (see Figure 12). The scenario was digitized by taking 240 thermal images and 24 scans at 8 scanning positions. The total thermal point cloud of the scene contains 116 million points. Figure 13 illustrates several views of the final thermal point cloud in which it can be seen an evident temperature gradient between different structural parts of the scene. A significant increase in temperature is clearly observed in the window frames since the rooms receive significant solar radiation. Floor and ceiling have a small temperature gradient with respect to the walls which leads us to think that that the floor is in contact with an interior space conditioned at a temperature higher than that of the room, and the terraced upper exterior space has received a large amount of solar radiation throughout the daytime.



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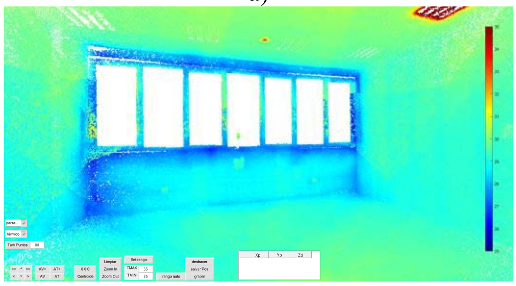

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Figure 10. Indoor thermal view of scenario 1. a) TPC of Session 1. b) TPC of Session 2

Figure 11. MoPAD2 in scenario 2.

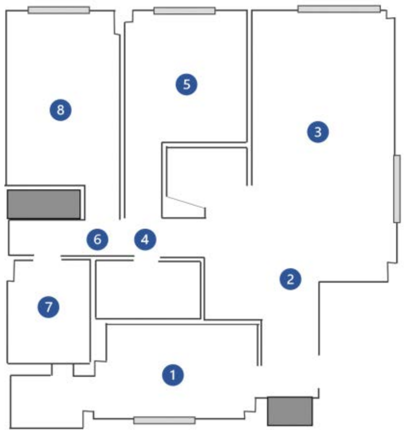
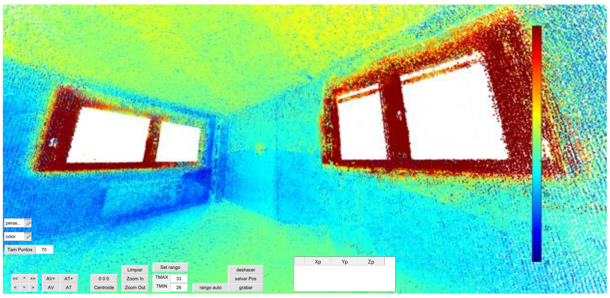



Figure 12. Floor plan of scenario 2 and stop locations in which the thermal scans have been taken.



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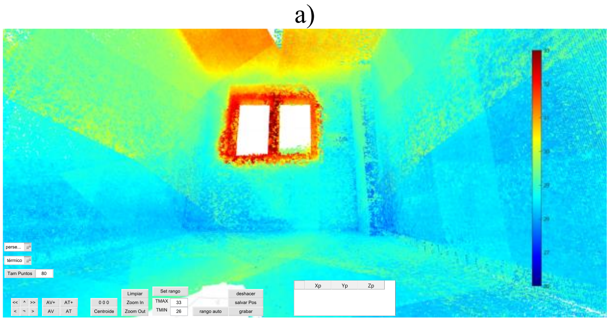

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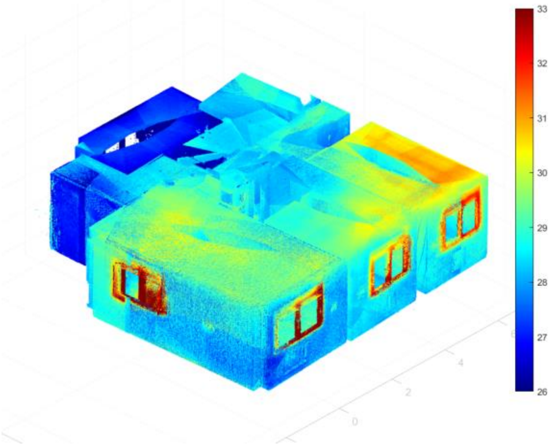


c)

Figure 13. a) A view of the TPC from scanning position 3. b) A view of the TPC from scanning position 8.[A3] c) External view of the TPC of scenario 2.

## 5 Conclusions

MoPAD2 is a small size robotic platform that has been developed with the objective of obtaining thermal point clouds of indoors of buildings. This platform overtakes, or at least reduces, some of the principal restrictions and limitations of the current similar thermal scanning platforms. Specifically, there are clear improvements in matters regarding power consumption, mobility and translation, autonomy, point cloud completeness, scene size and environment. Apart from these, the issue of multi-session thermal clouds is particularly addressed, which is a topic that has not been seen in much of the current bibliography, and in any case, only in 2D based approaches.

Programming and the integration issues have also been solved successfully under ROS and SDKs of different devices and sensors so that the platform is able to thermally digitize a wide variety of indoor scenarios. Thus, beyond a typical laboratory scene, MoPAD2 has been tested in various real-world environments such as official buildings and apartments.

In conclusion, it can be stated that a thermal point cloud of a building becomes a new monitoring tool that allows us quantitative and qualitative knowledge, and that the use of robotic platforms, such as MoPAD2, can be useful as a starting point for future improvements in this field of research.

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