SUITABILITY ASSESSMENT OF DIFFERENT SENSORS TO DETECT HIDDEN INSTALLATIONS FOR AS-BUILT BIM

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ABSTRACT:

Knowledge on the utilities hidden in the wall, e.g., electric lines or water pipes, is indispensable for work safety and valuable for planning. Since most of the existing building stock originates from the pre-digital era, no models as understood for Building Information Modeling (BIM) exist. To generate these models often labor-intensive procedures are necessary; however, recent research has dealt with the efficient generation and verification of a building's electric network. In this context, a reliable measurement method is a necessity. In this paper we test different measurement techniques, such as point-wise measurements with hand-held devices or area-based techniques utilizing thermal imaging. For this purpose, we designed and built a simulation environment that allows various parameters to be manipulated under controlled conditions. In this scenario the low-cost handheld devices show promising results, with a *precision* between 92% and 100% and a *recall* between 89% and 100%. The expensive thermal imaging camera is also able to detect electric lines and pipes if there is enough power on the line or if the temperature of the water in the pipe and the environment's temperature are sufficiently different. Nevertheless, while point-wise measurements can directly yield results, the thermal camera requires post-processing in specific analysis software. The results reinforce the idea of using reasoning methods in both the do-it-yourself and commercial sector, to rapidly gather information about hidden installations in a building without prior technical knowledge. This paves the way for, e.g., exploring the possibilities of an implementation and presentation in augmented reality (AR).

1. INTRODUCTION

The use of Building Information Modeling (BIM) is already common and primordial practice in the industry at various stages of a building's lifecycle (Pezeshki and Ivari, 2018), from its construction through its maintenance to finally a rebuild or potential demolition. In each of the phases, the BIM model can be beneficial, especially in the case of a rebuild, since all the built-in raw materials are known as well as no unanticipated problems can be encountered during the construction stage. A recent report exemplarily revealed that buildings are globally accountable for 39% of energy related carbon emissions: 28% are accrued in the course of ongoing operations, e.g., for conditioning and powering, and the remainder of 11% through materials and construction (World Green Building Council, 2019). Due to this grey energy, embodied in the building, more and more frequently a rebuild is opted for rather than for new constructions to reduce the carbon footprint of the building sector (Ürge-Vorsatz et al., 2020).

A comparatively large proportion of the existing building stock – at least in the European Union – dates from the pre-digital era (EU Commission, 2023) and was constructed using analog plans. These plans often no longer exist or the as-is state of the building has been repeatedly changed over time without keeping the blueprints up to date. This mainly concerns the hidden changes in the building, namely installations that are hidden in the wall, e.g., electric lines or water pipes. Generating knowledge about these utilities is important for both real estate companies and private owners. During renovation work or for installations affecting the wall, it is indispensable for work safety to possess information about the course of, for example, the electrical lines. The availability of such prior knowledge facilitates the whole planning process. Hence, the generation of as-built BIM models is also becoming an increasingly important and valuable task, which is, however, generally time-consuming.

The geometric structure of the building, e.g. the walls, can be

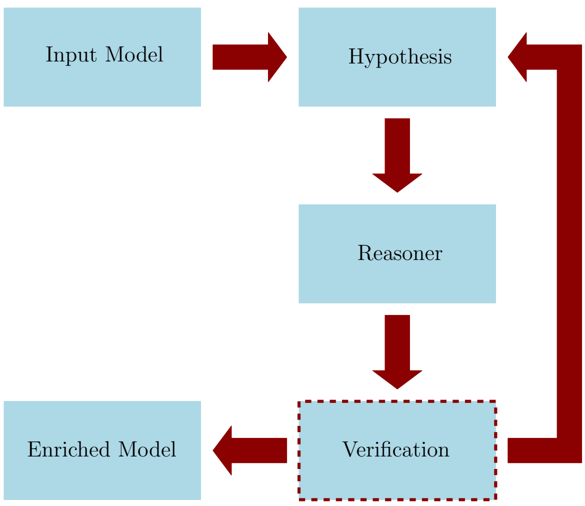

Figure 1. Procedure to obtain a model of hidden infrastructure in a building (Dehbi et al., 2022). The sensors examined in this article can be used for the iterative verification.

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assessed using techniques like laserscanning (Ochmann et al., 2019), nevertheless, obtaining knowledge on the hidden infrastructure is often a manually conducted and, hence, labourous process. In many countries the possible installation zones of electric lines, i.e., the parts of the wall where the installation of wires is allowed, are defined by a standard, e.g., for residential buildings in Germany by the DIN 18015-3[1]. Therefore, the search space is limited when assuming that the standard has been followed. Dehbi et al. (2022) proposed an incremental constraint-based reasoning, which at first generates a hypothesis for the electric installations (see Figure 1). In a subsequent step, point-wise measurements are proposed in order to incrementally verify or falsify the hypothesis, so that the user obtains a verified model of the installed electric lines with as few measurements as possible.

However, such procedures can only be effectively carried out if a sensor system is available which is appropriate for this specific application. The main contribution of this paper is the assessment of the suitability of different sensors to detect hidden installations for as-built BIM. To the best of our knowledge, it is the first attempt to reveal the installed and hidden electric network in walls based on systematic measurements. Therefore, in this paper a set of different sensors, consisting of low-cost and high-end devices performing either point-wise or area-based measurements is tested in a simulation environment. Even though the model of Dehbi et al. (2022) is for now only applied for electrical wiring, it is adaptable for other utilities like water pipes. Hence, the simulation environment in our laboratory also contains different pipes consisting of various materials with and without insulation. The point-wise measurement techniques can be directly tested, in contrast, the area-based measurement methods, i.e., a thermographic camera and a laser scanner with an integrated thermal image camera, rely on detecting temperature differences a posteriori. Therefore the electric lines are subjected to varying amounts of power, equally the pipes are filled with water at different temperatures.

The remainder of this paper is organized as follows: Section 2 offers an overview over relevant related research. In the subsequent Section 3 the set of different sensors (Section 3.1) and our designed simulation environment (Section 3.2) are presented. The conducted experiments and a discussion of their outcomes are presented in Sections 4.1 & 4.2. Section 4.3 provides an insight on the probability distribution of the electric line locations in the installation zones. Section 5 briefly summarises this paper and provides an outlook in open research questions.

2. RELATED WORK

As mentioned, Building Information Modeling describes the whole lifecycle of a building, from its construction over the maintenance to its renovation or destruction. In recent years, some countries have imposed the use of BIM as a mandatory requirement (Borrmann et al., 2020). Although the creation of the BIM model before or during the construction process is a well-studied procedure, the derivation of a model for an existing building (*as-built*) is an open research field. In this context, Volk et al. (2014) published a literature review on the state of research and the future needs. Information on the building's structure, e.g. the walls, is often gained with the help of point clouds stemming from a laser scanner survey (Ochmann et al., 2019). Bassier and Vergauwen (2020) presented a method for an unsupervised reconstruction of wall objects from point clouds. Romero-Jarén and Arranz (2021) used LIDAR measurements for an automatic segmentation and classification of different BIM elements. The interested reader is also referred to the study conducted by Pintore et al. (2020) which provides an overview on input sources, the structure of output models and a possible reconstruction pipeline as well as future research trends. Dehbi et al. (2017) suggested a stochastic approach to obtain a model from sparse observations rather than relying on conducting intensive surveying overhead.

Nevertheless, a BIM model consists of more than visually interpretable information, i.e., the installations hidden in the walls, such as electric lines or pipes. Krispel et al. (2017) use a laser scanner and panorama images taken by a camera to first obtain a model of the building itself. In a second step, a hypothesis for the routing of the electric lines is generated based on the visible electrical objects such as sockets and light switches. The hypothesis, however, is not verified. Dehbi et al. (2022) provide an incremental approach to generate a hypothesis based on the norms and standards for electric installations on the one hand, and to incrementally verify or falsify this hypothesis with as few measurements as possible on the other hand. In the end, the user has information about the true course of the existing electric installations.

To the best of our knowledge, there exist no other publications dealing with the detection of hidden utilities in the wall while assessing different measurement techniques. Nevertheless, thermal cameras are already used to detect thermal bridges in buildings (Costarelli et al., 2018) or inspect electric transmission lines and detect faults, e.g., for overhead cables (Ha et al., 2012). Some approaches employ autonomous systems with different cameras and sensors for the automatic detection and intelligent analysis of the state of transmission lines (Zhang and Dai, 2021). Other techniques exist for the detection of utilities in the ground, for example by utilizing ground penetrating radar (GPR) in combination with machine learning techniques. An overview over some of these approaches can be found in the review article by Amaral et al. (2022).

3. METHODOLOGY

3.1 Sensors for the detection of electrical wires

The ability to detect and localize electrical wires within walls is essential for occupational safety as well as efficiency. Maintenance and extension of electrical lines in older buildings with missing or unreliable plans can become extremely laborious and, hence, expensive. To find existing installations in walls different sensor principles can be applied. Each of it has an optimal application case due to individual strengths and weaknesses. In this section we compare four technical approaches:

1. Magnetic sensor

   The magnetic sensor is a low-cost system that is often applied by a handyman. In a compact housing, a magnetic generator is combined with a response sensor. The sensor system is directly applied to the wall where the generated magnetic field interacts with metal objects in its direct surrounding. This interaction is indicated by sound or optical signal but the threshold has to be calibrated at a comparable wall without metal objects. This approach is able to

[1] https://www.din.de/en/getting-involved/standards-committees/nabau/publications/wdc-beuth:din21:257423669

Device	Price	Measurement principle	Measurement type	Measurement object
Walabot DIY	110 USD	microwave sensor	point-wise	pipe and wire, metalstud, wooden stud, no object
Bosch GMS 120	100 USD	magnetic sensor	point-wise	magnetic metal, non-magnetic metal, non-metallic objects, live electric line, no object
VarioCam HD research 900	37000 USD	thermographic camera	area-based	temperature differences
Leica BLK 360	22500 USD	thermographic camera	area-based	temperature differences

Table 1. Overview on the used sensors and their characteristics.

detect electrical wires as well as water and gas installations. Unfortunately it can also interact with other metal components in the wall that have the potential to cover the objects of interest.

2. Microwave sensor

   Closely related to radar technology, electromagnetic waves are transmitted by the underlying sensor and reflected by the wall itself as well as by objects within the wall. The complex signal response is then analyzed by a software and different materials can be distinguished. Systems used for, for example, electrical wire inspection need to be applied directly at the wall and mostly do not support imaging.

3. Electrical transmitter and receiver

   A more advanced system is based on a separate transmitter that modulates a high frequency signal to a specified electrical wire and a receiver that is able to detect this. They are not attached so that the transmitter can be attached to a wall plug and the receiver can be used to find the corresponding wire in the whole building.

4. Thermographic camera

   The application scenarios of thermographic cameras are similar to transmitter and receiver systems. Here, a specific wire is marked by setting significant electrical power to a plug. The wire heats up and can be detected by the increased wall surface temperature. Same is possible for water pipes using hot or cold water. Hence, the thermal camera is a passive measurement system. The main advantage is the spatial resolution of the camera allowing a quick search for a wire on a larger wall at a distance of several meters.

3.2 Simulation Environment

For data privacy reasons with the related restrictions and due to the frequent lack of information on the true (*as-is*) state of the hidden installations, an evaluation environment has been designed and built in our laboratory to determine the reliability and robustness of the sensors, which is displayed in Figure 2. Another advantage of this setup is that it enables the variation of various parameters, such as the depth at which the electric line is placed or the temperature of the water contained in the pipes. Hence, it is possible to analyze the capabilities of the sensors under controlled simulation conditions.

The environment is built using a dry construction method, which is challenging for detection devices, e.g., due to the stud frame which can possibly influence the measurement results. The structure measures 1.2 $\times$ 1.8 meters and features a planking of gypsum plasterboard with a thickness of 1.25 cm. The lower half (grey) is double planked, whereas the upper half consists of just one panel. A grid is drawn on the surface to facilitate the localisation and evaluation of the measurements. The respective arrangement of wires and pipes is identical in construction in the single and double planked area. The vertical bars are made of either wood or aluminium. The electric cable (red-dashed) is a three-core, conventional electrical cable of 1.5 mm^2, which complies with *NYM-J 3x1.5* in German standard. In the areas outside the vertical bars, the cable lies directly beneath the plasterboard; between the bars it remains 5 cm distant from the wall. The power on the cable can be varied using different consumers up to a maximum of 3500 Watt.

The pipes (blue) are either made of copper or composite plastic or they consist of galvanised steel. They have a length of 40 cm, a diameter of 15 to 20 mm and are assembled at a distance of 5 cm from the wall. For each of the pipes the lower half is insulated by mineral wool with aluminium lamination. The pipes can be filled with water of varying temperature.

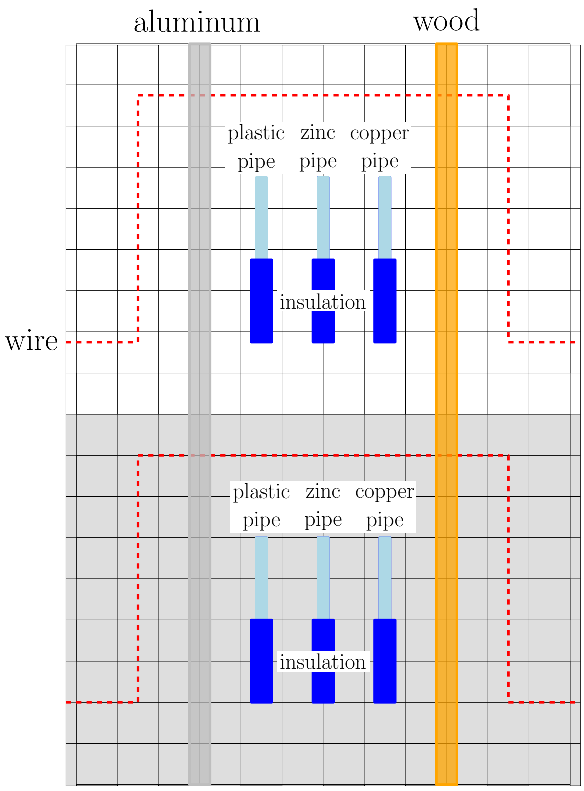
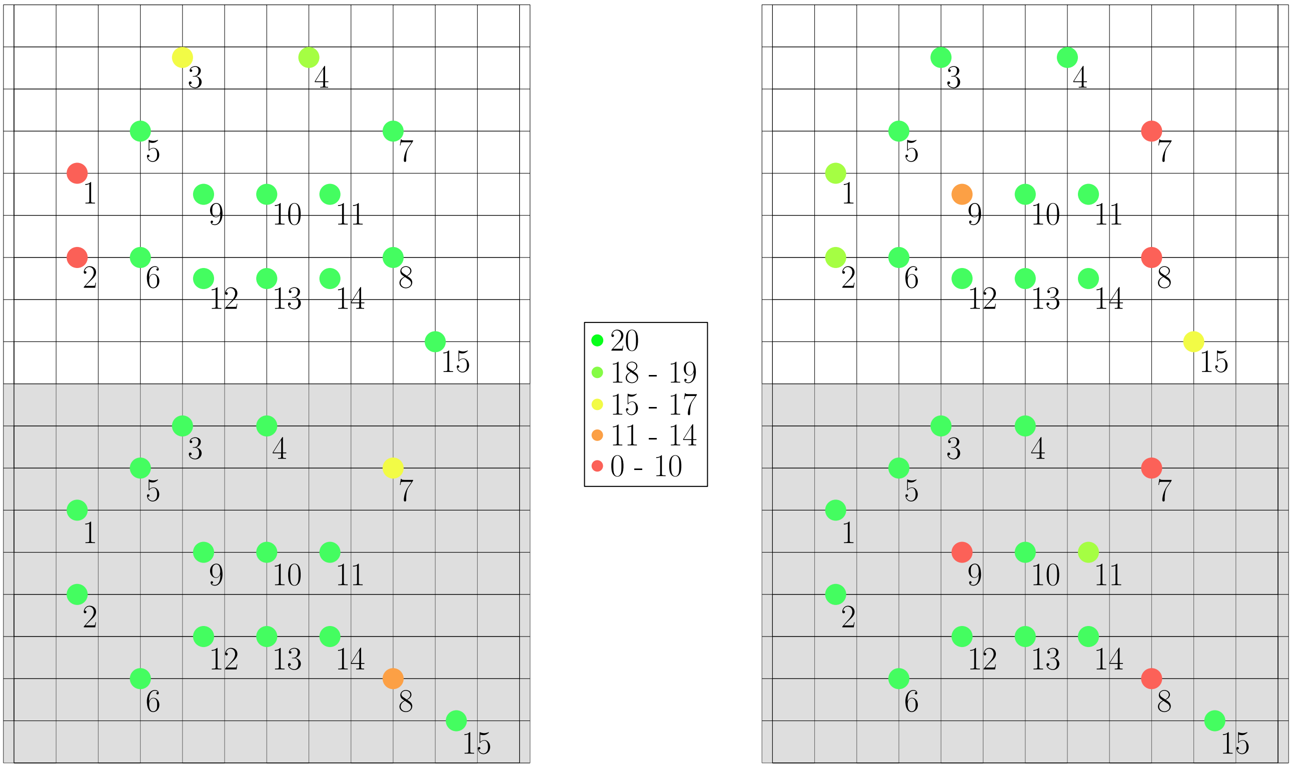


Figure 2. The simulation environment used for the experimental evaluation. The grey area is double planked, whereas the white area consists of only one panel.



(a) (b)

Figure 3. Results of the point-wise measurements with the *Walabot DIY* (a) and the *Bosch GMS 120* (b). The number of correct measurements is indicated by the colour of the circles.

4. EXPERIMENTS AND RESULTS

4.1 Point-wise methods

In the experiments, four different sensors, which are listed in Table 1, were investigated. The *Walabot DIY*[2] is a microwave sensor from the low-cost segment, it comes at a cost of approx. 100 USD. It can be linked with an Android device to depict the recorded data. The sensor performs point-wise measurements and can distinguish between different materials, i.e., pipe or wire, metalstud and wooden stud. The manufacturer specifies a maximum locating depth of 100 mm.

With the point-wise sensors, a series of measurements was conducted at the points depicted in Figure 3. The measurement points (mp) either lie above a wire (mp 1 – 4), or above the studs (mp 5 – 8), the different pipes (mp 9 – 14) or even on a portion of the wall without any detectable material beneath (mp 15). Each point was measured 20 times. The coloration indicates how often the correct material was detected. The results for the *Walabot* are shown in Figure 3a, the normalized confusion matrix corresponding to the measurements can be found in Figure 4. The aluminium stud, which directly lies beneath the measurement points 5 & 6, and pipes (mp 9 – 14) were detected correctly regardless of the insulation. The wooden stud, represented by measurement points 7 & 8 was well detected in the single planked area, the double planking led to some measurements identifying no object at all. However, when considering the topic of the paper this is not a crucial mismeasurement, as no electric line or pipe was displayed either. The electric lines (mp 1 – 4) were detected correctly again in the double planked area. With a single plank, at the points where the line is directly attached to the wall (mp 1 & 2), the sensor in most cases is not able to detect the wiring, but indicates a wooden stud instead. Additionally, it is possible to compute values for *precision*, i.e., how often the detected material is correctly detected, and *recall*, i.e., how often the actually present material is detected, for the individual classes from the repeated measurements of the different measurement points. For the most relevant class pipe or wire we obtain a *precision* of 100% and a *recall* of 89%. This implies that a measurement showing pipe or wire is always correct, in contrast in 89% of the measurements a pipe or wire is detected if it is actually present. Nevertheless, the latter value is highly influenced by the aforementioned problems at the measurement points 1 and 2 in the single planked area.

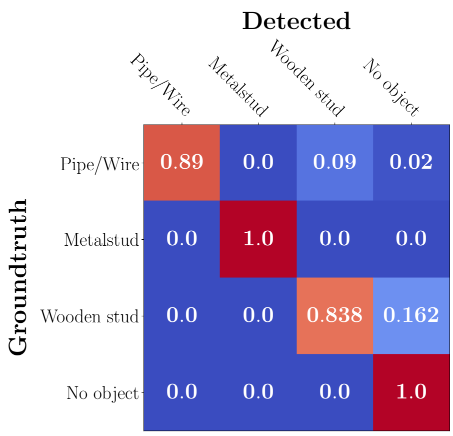


Figure 4. The normed confusion matrix of the measurements with the *Walabot DIY*.

[2] https://walabot.com/products/walabot-diy-1

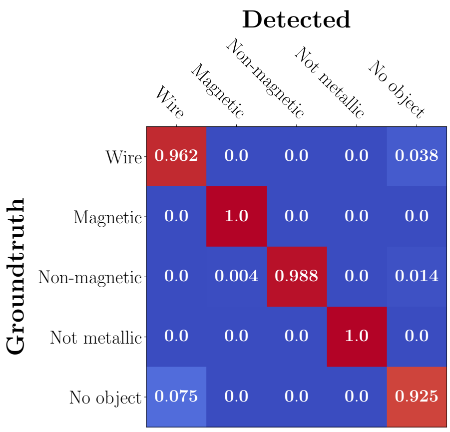


Figure 5. The normalized confusion matrix of the measurements with the *Bosch GMS 120*.

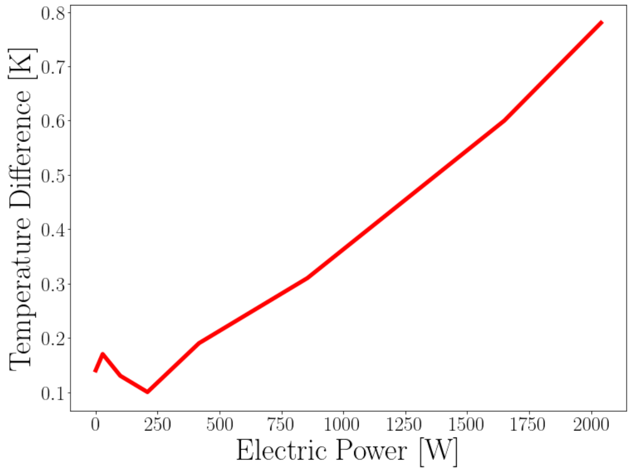


Figure 6. The measurable temperature difference between the wire region and its immediate surrounding.

The *Bosch GMS 120*[3] is also a low-cost sensor (approx. 110 USD) which likewise carries out point-wise measurements, but, in contrast, relies on a magnetic sensor. Additionally, the sensor is able to distinguish between even more materials, i.e., magnetic and non-magnetic metals, non-metallic objects and live electric line. The specified location depth varies between 38 mm for wood and 120 mm for magnetic metals. For electric wires the location depth is indicated with 50 mm.

The results for the *Bosch GMS 120* are shown in the normalized confusion matrix in Figure 5 and graphically in Figure 3b: The wooden stud (mp 7 & 8) is mostly not detected as any object, but, as aforementioned, this is not a crucial error regarding the scope of the paper, to find electric lines or pipes. Moreover, the uninsolated composite plastic pipe, which should be detected at measurement point 9, is misinterpreted as magnetic metal object (double planked area) or non-magnetic metal object (single planked area). All other measurements yield the expected results. In the experiments, we obtained a *precision* of 92.5% for wire with a *recall* of 96.2%. Magnetic and non-magnetic pipes have been detected with a *precision* of 99.6% and 100%, respectively. The corresponding values for the *recall* are 100% and 98.2%.

All in all, the point-wise measurements yield satisfactory results in detecting wires and pipes, nevertheless, the *Bosch GMS 120* outperformed the *Walabot* in our experiments, since it detects the electric lines more reliably and only has drawbacks in detecting the wooden structure, which is not particularly important for our experiments.

4.2 Area-based techniques

As shown in Table 1, the *VarioCam HD research 900*[4] is a thermal imaging camera with a detector format of 1024 × 768 pixels. The measuring range lies between -40 and 2000 °C with a resolution of 0.02 K at an air temperature of 30 °C. The area-based sensor yields images with temperature information as result. These images can be evaluated with the software package *IRBIS3*[5].

[3] https://www.boschtools.com/us/en/boschtools-ocs/stud-finders-detection-devices-gms-120-35140-p

[4] https://www.infratec.eu/thermography/infrared-camera/variocam-hd-research-900

[5] https://www.infratec.eu/thermography/thermographic-software

The result, however, is not directly a position of, e.g., a cable, but has to be further processed by a user. Since the camera only measures temperature, the temperature of the cable or wire has to be manipulated in order to detect them via temperature differences compared to the immediate surrounding. For electrical wires, the experimental layout comprises a tunable electrical hair dryer and a power meter. For testing purposes a stone wall scenario was used first. The electrical devices were attached to a wall plug and used at different amounts of power. The measurable temperature difference between the wall with wire and wall without wire has been noted for a power between 100 and 2100 W in Figure 6. It turned out that starting at approx. 1500 W, the temperature difference exceeds 0.5 °C which is also detectable by cheaper thermographic cameras.

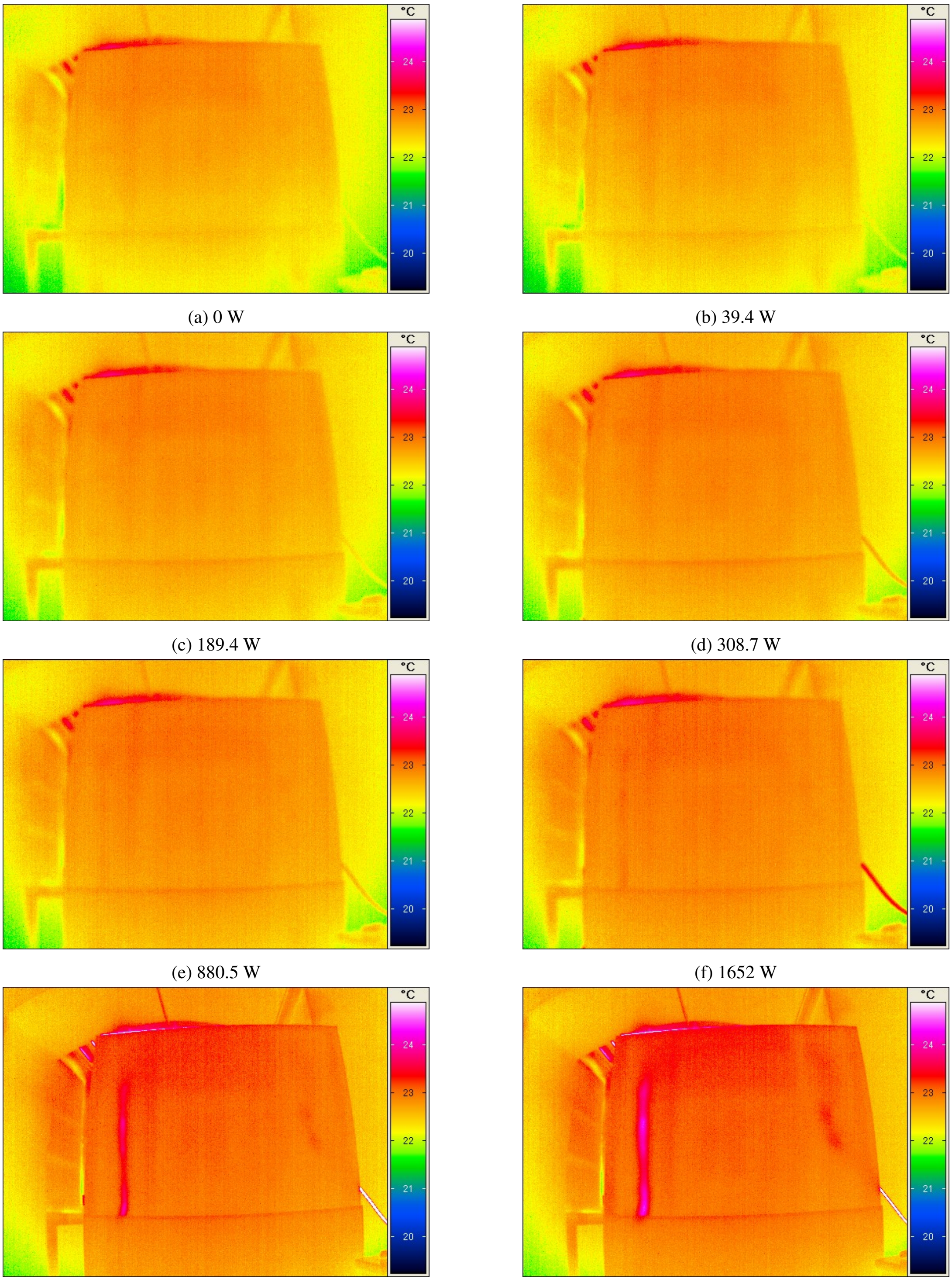
Results of the measurements for different amount of power are shown in Figure 7. It can directly be seen that the electric lines become visible with a power of 880.5 Watt. However, the wire can only be seen completely with 3500 Watt, and even better after waiting for another 5 minutes. Using the evaluation software it is possible to place measurement points on the recorded image to determine the temperature difference between the surrounding wall and the possible line itself. In the double planked area, the visual detection is harder; however, at latest by means of the evaluation software, the recognition of the lines is possible.

To detect the pipes, they have been filled with cold (19 °C) and warm (58 °C) water to evoke a temperature difference. While the cold water only causes a small temperature difference, which is nevertheless visible and can also be recognized in the evaluation, the warm water increases this significantly (see Figure 8a). In the double planked area the heat signature is blurred and the pipes are only detectable by the evaluation software (see Figure 8b).

All in all, the *VarioCam* thus allows the detection of both electrical lines and water pipes. To achieve this, however, they have to be heated or set under power. Thereby, a high amount of power over a longer period of time is necessary for a more reliable detection.

The second thermal imaging sensor is a built-in thermographic camera of the *Leica BLK 360*[6] laser scanner. It is reasonable to

[6] https://leica-geosystems.com/en-us/products/laser-scanners/scanners/blk360

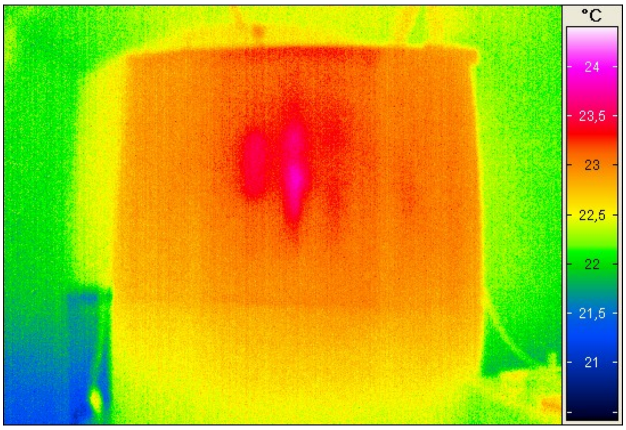


(a) 0 W (b) 39.4 W
(c) 189.4 W (d) 308.7 W
(e) 880.5 W (f) 1652 W
(g) 3500 W (h) 3500 W after 5 minutes

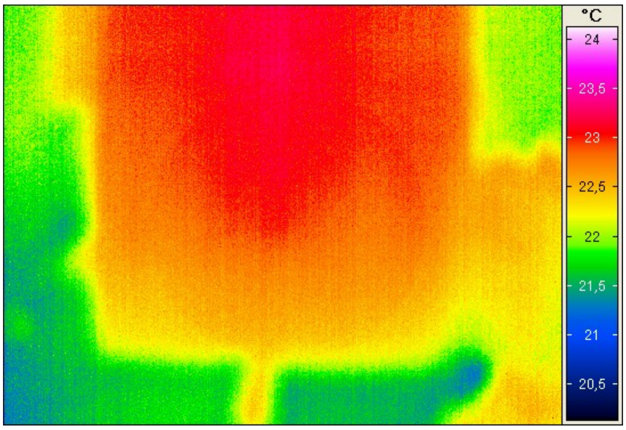
Figure 7. Results of the *VarioCam* measurements with different amount of power on the electric wires in the single planked area of the simulation environment.

test this device, as it is often used for the surveying process and, as mentioned in Section 2, the subsequent creation of a BIM model. Hence, a coupling of both processes, the derivation of the general structures and a simultaneous enrichment with the utilities hidden in the wall would be promising. Nevertheless, since the focus of the instrument does not lie on the thermal imaging camera, it is significantly more limited in terms of the specifications. The measuring range lies between -10 and 65 °C, the resolution amounts to 0.05 K. Although these specifications are sufficient for the application, the detector format, however, is significantly smaller with only 160×120 pixels. In addition, the images can only be layered over the point clouds in the scan software, but no software for a further evaluation of, e.g., temperature differences is available. Hence, the electric lines must be clearly and directly visible for the user, i.e., the temperature difference has to be larger.

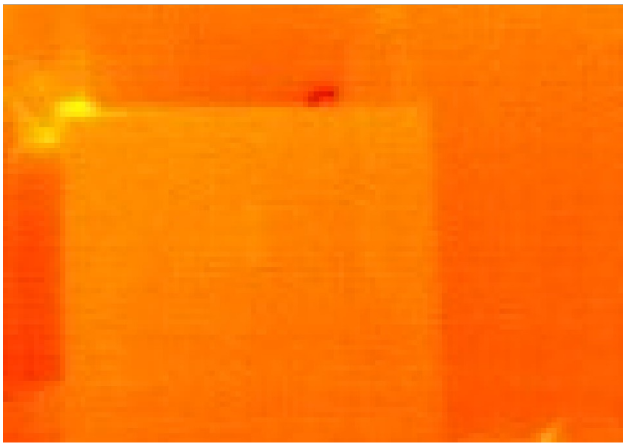
The results of our experiments reveal that this device is not suit-



(a) *VarioCam* recording pipes filled with warm water in the single planked area



(b) *VarioCam* recording pipes filled with warm water in the double planked area



(c) *Leica BLK* recording pipes filled with warm water in the single planked area

Figure 8. Results of the measurements with pipes filled with warm water.

able for this use case. In the double planked area neither the electric lines nor the water pipes are visible to the bare eye. Even in the single planked area, only the wire which is mounted directly behind the wall is recognisable, and even that only with a power of 3500 W (see Figure 9). The pipes are again not visible (cf. Figure 8c). As aforementioned, no further analysis software is available, hence, these hidden utilities are not detectable at all.

All in all, the dedicated thermographic camera (*VarioCam*) is

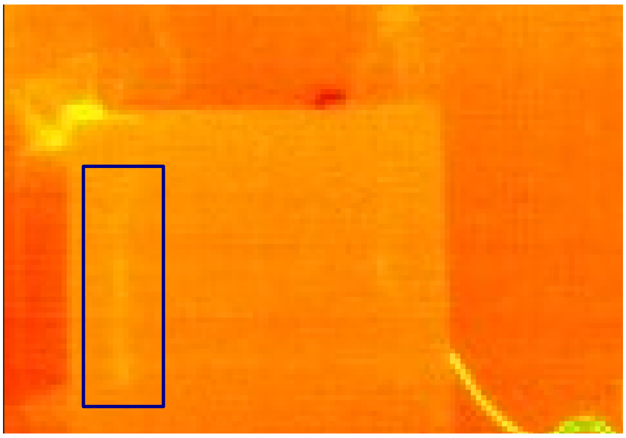


Figure 9. Result of the *Leica BLK 360* with 3500 W. One electric line is slightly visible within the blue rectangle.

suitable for detecting electric wires in the wall and under certain conditions it can also be used to detect pipes. The laser scanner, in contrast, is not capable to provide satisfactory results. However, for the area-based techniques a subsequent evaluation is usually required, whereas the point-wise measurements are able to directly provide a result. Additionally, in a real-world scenario, it is not sufficient to use just one socket to find out where the electric lines are installed. That is because there are typically several different circuits that supply different consumers. Hence, for a complete picture, all sockets have to be used with a certain amount of power, either simultaneously or one after the other, which again significantly increases the measurement effort and can quickly negate the supposed advantage of this area-based measurement technique.

4.3 Distributions of electric lines

Since the norms and standards only define an installation zone, e.g., in Germany with a width of 20 to 30 cm, the specification as a point-wise measurement at the preferred installation point of this zone is somewhat simplifying. Nevertheless, a sampling in several buildings shows that the lines are actually mostly located at the preferred installation dimension of the respective zone. This can be exemplary seen in Figure 10, which shows the distribution of the electric lines in the installation zone that spreads next to a door generated via *Gaussian Mixture* fitting. This particular zone is 10 to 30 cm distant from the door, with a preferred installation point at 15 cm. The *Gaussian Mixture*

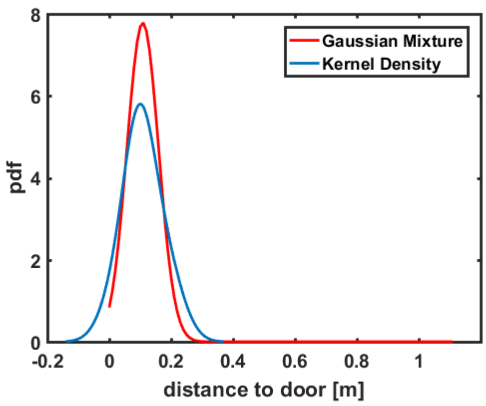


Figure 10. Probability density function (pdf) of the installed electric lines with respect to the distance to the adjacent door.

has been approximated using a *Kernel Density Estimation* in a non-parametric fashion. It can be seen that the peak is indeed at 15 cm. Such distributions could be projected on the wall model in order to restrict and visualize the area and zones of interest where a hypothetical line could be part of.

5. CONCLUSION

This paper introduced an assessment of the ability to detect hidden infrastructures in the wall, e.g., electric lines and water pipes, for different sensors. The latter can be distinguished into point-wise and area-wise sensors depending on the measurement principle. Our experiments reveal that the point-wise measurements perform well in detecting the utilities hidden in the wall. Also high-end thermographic cameras are capable of detecting electric wires and water pipes. Nevertheless, they have to be set under power or be filled with warm water to evoke a temperature difference which is detectable. Since the amount of power has to be very high for reliable results, and the evaluation has mostly to be done retrospectively via software tools, the application of this device is not particularly practical.

The results reinforce the idea of using methods such as the reasoner from Dehbi et al. (2022) in both the do-it-yourself and commercial sectors to rapidly gather information about hidden installations in a building without prior technical knowledge. This paves the way for, for example, exploring an implementation and presentation in augmented reality (AR) where the operator will be able to perform the verification process and visualize the results in an incremental fashion. Even though drywall construction is often used, for the sake of generalizability of the results other materials, e.g., solid concrete walls, will be subject of a subsequent study. The acquired measurements from the simulation environment opens up new opportunities to integrate probabilistic knowledge in the reasoning procedure from Dehbi et al. (2022) which will be subject of future work.

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