Reflectance Transformation Imaging for Detecting Knots in Heritage Timbers

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Abstract

Reflectance Transformation Imaging (RTI) is a common technique used in different cultural heritage applications. Images of an object or a part of an object are captured using a fixed camera position but changing lighting directions. With this technique small details can be captured, revealed by their shadows, even if the camera resolution would not resolve them. In this contribution we used RTI to support the detection of wooden knots in heritage timbers. We developed a handheld low-cost RTI dome that fits to create RTI models of wooden beams. To locate the knots in the context of their surroundings, 3D models were created via Structure from Motion (SfM) based on the RTI images. We used three different subsamples of the RTI images to optimize our workflow and analyse the possibilities of using different illumination setups. The models then were compared with a model that was created using common camera equipment. The models were compared based on geometry and colour. Our two case studies are addressed to a historic roof framework in a church in Bamberg (Germany) and, in addition, to more accessible newer wooden beams.

1. Introduction

The size, amount and position of wooden knots in timber are important evidence for strength and grade class estimation. Detecting these knots is a difficult task, especially for historic timbers, because of paint, dust and change in colour over time. The appearance of the knots changes with the lighting conditions so that some of them are better visible under a certain illumination which is hard to choose on the spot. Reflectance Transformation Imaging (RTI) solves this problem by enabling a flexible virtual illumination of the images respectively RTI models afterwards. Multiple images from a fixed camera position and controlled varying illumination are imperative in order to generate an RTI model. Even common photogrammetric equipment can be used for the data acquisition despite clear practical advantages of tailored hardware. For this reason, we apply a self-developed low-cost RTI dome to capture the knots. However, the RTI model is not georeferenced, hence knots cannot be located with respect to the beam coordinate system. We are solving this by using the RTI images in a Structure-from-Motion (SfM) pipeline. Since the computing time increases with the numbers of images, we have tested different subsamples of the RTI images to optimize our workflow and the quality of the 3D models. Subsequently, the resulting 3D models are compared and analysed based on colour and geometry with respect to a common reconstruction method using a DSLR camera. We have tested our method in two case studies. The first one is a historic roof framework of the Dominican Church in Bamberg (Bavaria, Germany). The second one is a wooden beam at the Jade University of Applied Sciences.

The main contributions in this paper are:

- The presentation of our self-developed low-cost RTI dome that is handheld and therefore applicable for diverse applications.
- The evaluation of RTI images for SfM and the comparison with conventional photogrammetric equipment including different subsamples for the optimisation of the workflow.

The following sections are organised as follows: After a brief explanation of the basic principles of RTI and the usage of RTI domes, we describe our RTI dome and our conducted experiments. Next, we present our two case studies and the results of our experiments. We conclude our work with a discussion and possible approaches for future developments.

This work is part of the WoodF(ea)uture project. In this context an AI pipeline for the detection of wooden knots based on a pre-trained YOLOv8m model is developed (Pan et al. 2025).

2. Related Work

Reflectance Transformation Imaging uses multiple images of a fixed camera position under controlled varying lighting directions. Small structural changes on the surface of objects can be revealed by their (varying) shadows. Through the combination of these images an interactive model can be created that enables freely selectable lighting directions by interpolation (Coules et al. 2019). RTI was developed based on Polynomial Texture Mapping (Malzbender et al. 2001) and is a common technique in the field of cultural heritage and archaeology because it enables a more complete documentation of objects for later analysis. Besides the colour impression of an object that can massively change based on the lighting direction, surface normals can be calculated characterising the topography of the surface. RTI can be applied using common camera and lighting equipment, but it is preferable to use dedicated hardware including a dome for faster data acquisition and to prevent influences by external light sources. General examples of RTI applications are the capturing of carvings on small objects like pipes or stamps, but also on larger objects like gravestones (Mytum and Peterson 2018).

Wilk et al. (2024) constructed a dome including 120 LEDs with an exchangeable camera to create RTI models of small moveable objects like amphoras and pottery. They compared the results of high-quality and miniature cameras and validated that the quality of miniature cameras can be sufficient for archaeological objects. Their system is highly automated and does not need external equipment like laptops but must stand on the ground and cannot be handheld to capture data of immovable objects.

Gotsikas et al. (2025) use an RTI dome to digitize epigraphic squeeze. They enhance the visibility of reliefs. The dome has a diameter of 3 m, contains 32 LEDs and costs 600 € to build plus 600 € for the installed camera.

Lemsle and Bigerelle (2024) present MorphoLight. It is a customisable RTI device based on an Arduino and a Raspberry Pi with a diameter between 40 mm and 350 mm considering the recommended hardware. MorphoLight is portable and was tested on an oil painting.

3. Method

We used the RTI dome presented in Richter (2025) for data acquisition (Figure 1). The dome was made from six sections that were 3D printed. Each section consists of six LEDs so that 36 lighting directions can be realised. The LEDs are controlled by an Arduino Nano which is connected to a Raspberry Pi 5. The Pi controls the Arduino and the HQ camera module so that lighting and image acquisition are synchronised. The whole RTI dome is powered by a power bank and therefore freely movable. Because of its lightweight design the dome can be used handheld. The cost of materials is around 250 €. Additionally, a laptop computer is needed. The computer connects wireless to the Pi via Secure Shell Protocol (SSH). The data acquisition can be started, and the images can be viewed with the laptop. Each acquisition consists of 36 images. For each image only one LED is turned on. Based on the images RTI models can be calculated using the RelightLab application developed by the Visual Computing Lab (n.d.) and recommended by the Cultural Heritage Imaging (CHI) Organisation (CHI, n.d.). The RTI models can be viewed using the CHI viewer and different rendering methods like specular enhancement can be used to improve the visibility of structures even more. When using a hemispherical arrangement of LEDs, as in this study, the Hemispherical Harmonics is a suitable polynomial basis function (Happa et al. 2010).

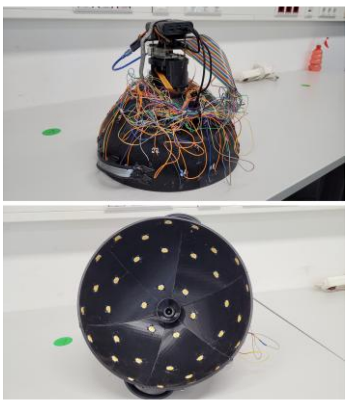

Figure 1: RTI dome from the outside (top) and the inside (bottom).

Prior to the data acquisition for the creation of the RTI models the lighting directions must be calibrated. For this purpose, a method was used as described in Mudge et al. (2006). Two black spheres with polished surfaces were placed under the dome (Figure 2). The light of the LEDs is reflected by the spheres and creates a hotspot on each surface. These hotspots can be extracted, and based on that the directional lighting vector of the actual LED can be calculated. After the calibration the lighting vector of each LED is known and can be used for the creation of RTI models without spheres needed in the following measurements.

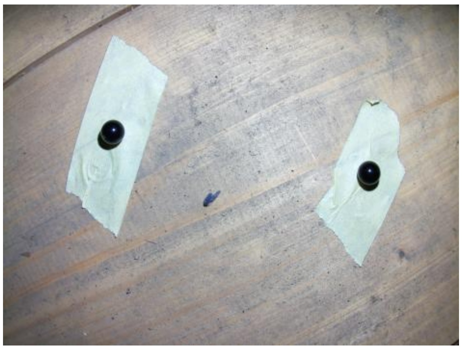

Figure 2: Two black spheres under the dome for the calibration measurement (Richter 2025).

To spatially locate the knots and get a better understanding of the relationship of knots, the structure and load capacity characteristics of the beams, we used the dome to capture images of the wooden beams with a high overlap. This way we can also use the images for SfM and locate the wooden knots on the beams in the 3D model. Furthermore, we captured an additional image during the data acquisition with six LEDs turned on to get an evenly illuminated image (Figure 3). From this data we define three different datasets. Dataset A consist of all images for the creation of the RTI models plus an additional image with 3 LEDs. Since there are 37 images for each RTI model and multiple RTI models to capture one beam, the number of images increases rapidly with the size of the captured area and therefore the calculation time. With the goal to reduce the calculation time, we only use a subsample of all images in dataset B. Six images with highly different lighting directions for each position of the RTI dome were chosen. The lighting directions are the same as the used LEDs for the evenly illuminated images. These images are used in dataset C. For each dataset we generate individual 3D models. For reference, we created a fourth dataset D with a high-quality DSLR camera (Table 1).

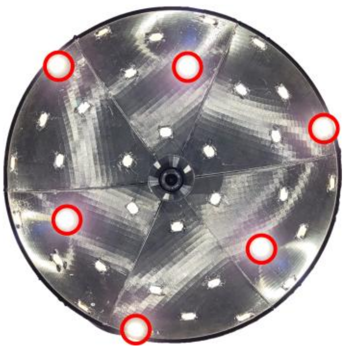

Figure 3: The six LEDs that are used sequentially for dataset B or simultaneously for dataset C.

Dataset	Device	Description
A	RTI dome	All 37 images from each position, each image with one LED activated plus one image using three LEDs simultaneously
B	RTI dome	6 images from each position, each image with one LED activated
C	RTI dome	One image from each position using 6 LEDs simultaneously
D	DSLR camera	Common image sequence with diffuse external lighting

Table 1: Description of the four used data sets.

We compare the models of the datasets regarding the number of images, the number of points, the mean point spacing, the visual appearance and the intensity. We define the intensity as the mean of the three colour values in the RGB colour space. The mean point spacing is calculated by considering the distance between each point and its nearest neighbour.

4. Results

We tested our system in two case studies. The first one is the historic roof framework of the Dominican Church in Bamberg, nowadays used as an auditorium by the University of Bamberg. Beams appear in their natural surface but covered with dust and dirt. Parts of the framework were built around 1400 and therefore must be tested for strength and stability to ensure safety. For the second case study a black-painted wooden beam at the Jade University of Applied Sciences is used. The wood is much younger but easier to access and therefore suitable for specific evaluations. In both cases wood knots are present at the surface but difficult to detect because of dust and layers of paint (Figure 4).

Figure 4: Heritage roof framework in Bamberg (top) and the wooden beam at the Jade University of Applied Sciences showing diffuse lighting of dataset D (bottom).

4.1 RTI Models

The RTI models can capture the characteristics of the wooden knots. Different lighting conditions emphasise different aspects of the structure. Furthermore, using the visualisation *specular enhancement* the different structures are shown even better (Figure 5).

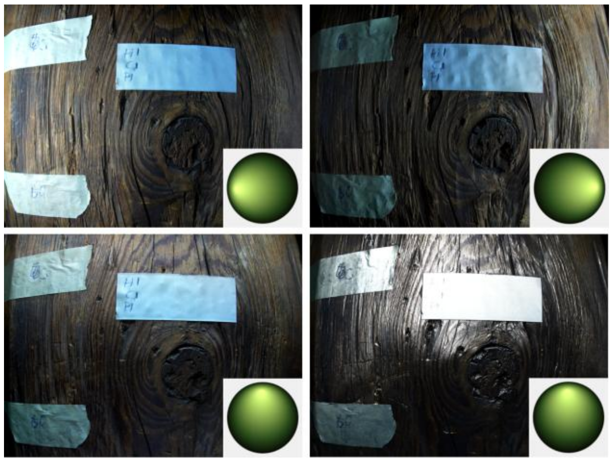

Figure 5: A wooden knot under different virtual lighting conditions, the green spheres show the lighting direction, the bottom-right image is specular enhanced.

4.2 Calibration and Scaling

A timber of the historic framework was recorded from 46 image stations (90% overlap) in a strip-wise configuration. It can be shown that SfM (Agisoft Metashape) is capable to create 3D models of the surface. In the first attempt, the geometric model of the timber was deformed since the Metashape camera calibration could not compensate for the fisheye properties of the RTI camera. After preprocessing with fisheye image rectification based on a chessboard pattern, the resulting 3D model is correct and ready for further processing (Figure 6).

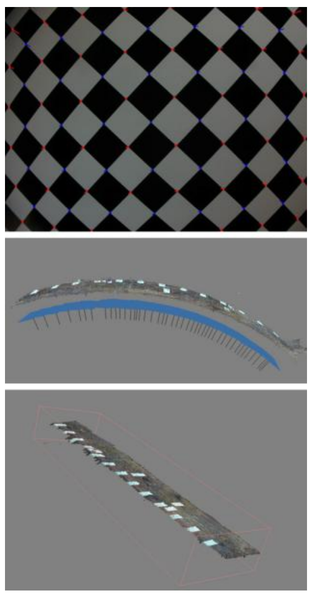

Figure 6: The used chessboard pattern (top), the deformed 3D model (middle) and the corrected 3D model (bottom).

We also used this calibration method for our second case study to calibrate the cameras for the datasets A, B and C. For the reference dataset D, we used a Nikon D850 with a 24 mm lens and create a 3D model with a common SfM pipeline. It is worth mentioning that we have used multiple scale bars to scale the model based on the images of the Nikon D850 but only one scalebar to scale the models based on the RTI images. Thus, the given length of that one scale bar determines the scale of the model based on the RTI images. The difference of the same scale bar between the models and the reference is 0.2 mm.

4.3 3D Model Comparison

We created four 3D models based on the four datasets and compare the results based on a wooden knot (Figure 7). All point clouds are shown under the same virtual lighting conditions in the 3D view of CloudCompare. The heights refer to best-fit planes computed for each model individually in the area marked red in Figure 7. Beside the visual comparison we show some descriptive parameters of the models and the data (Table 2). It is to mention that some of the RTI images were corrupted during the data transfer so that the number of images in dataset A and B are not a multiple of 37 respectively 6 exactly.

A difference in colour is recognizable between the four models. This was expected because of the different lighting conditions during the image acquisition. For dataset A shadows on the texture can be seen. The reason for that could be the huge number of images with different lighting conditions. In each image are different shadows and some of them are projected onto the texture of the 3D model causing little artifacts. Dataset B leads to the darkest texture, probably because of the chosen LEDs. Three of them are in the upper part of the dome and only three on the bottom rim. The brightest texture is shown in dataset C. Using six LEDs at once, good illuminated images are created. In comparison to Dataset D, the images might even be a little bit overexposed. These visual observations are supported by the mean intensity of the points. Since Dataset D was acquired using a DSLR and diffuse lighting as common in SfM processing, the colour of D could be titled as "correct" colour. Furthermore, a colour-calibration was conducted for Dataset D in order to get a realistic model of the dark beam.

The geometries of the four models are similar. The same coarse structures can be seen. Dataset A and B seem smother and show less noise than dataset C and D. That might be caused by the higher number of images but could also be an effect of different lighting. Differencing these two influences is barley possible to this stage but could be part of our future work. Even though a low-cost camera and intuitively poor (because varying and direct) illumination were used, the results of Dataset A and B look very promising. The differences from the best-fit plane are similar for all datasets, which shows, that all used setups are capable to reconstruct even fine details of the knot. The number of points of dataset D is the highest and therefore the mean point spacing is the smallest.

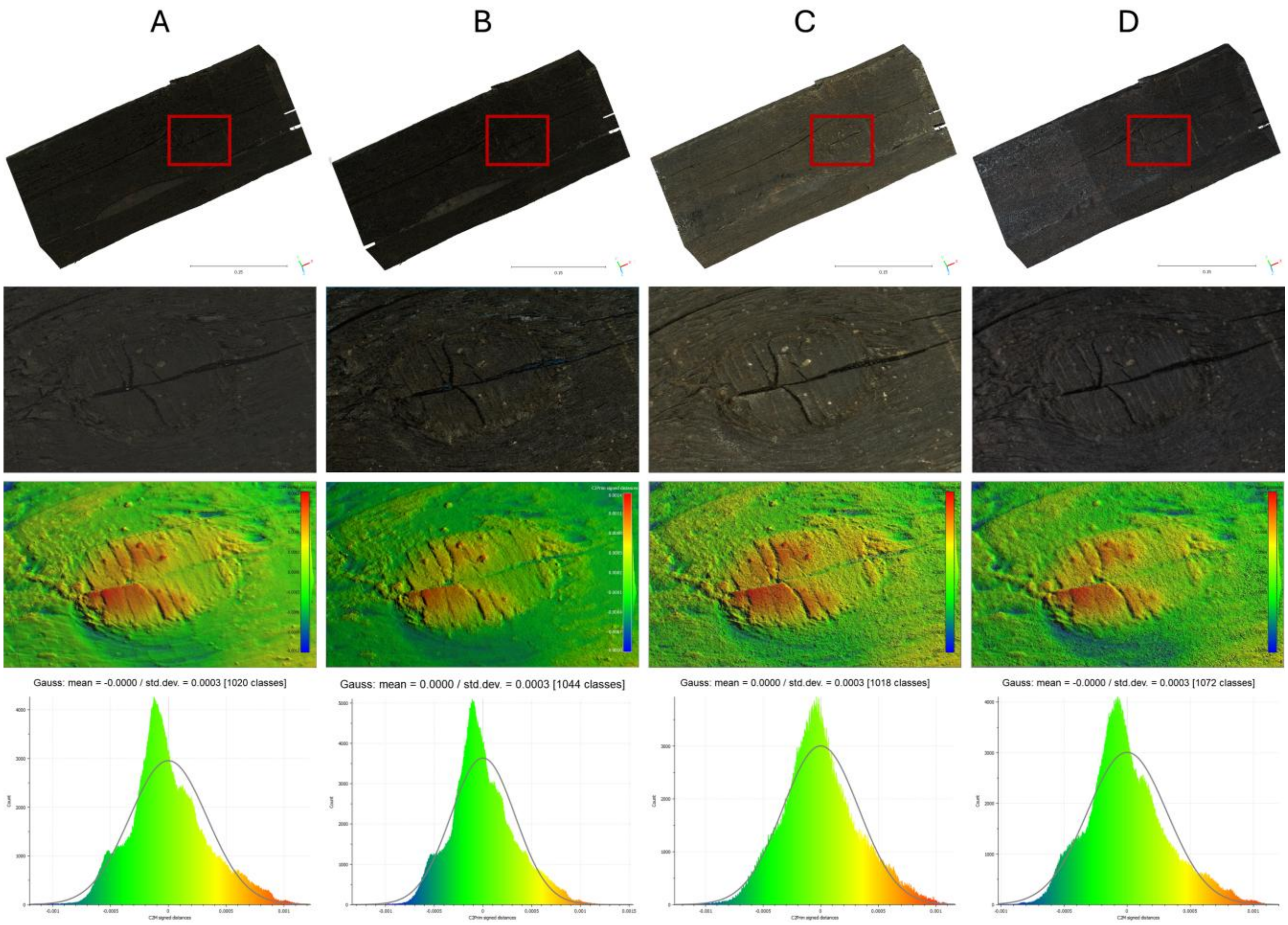

Figure 7: Comparison of the 3D models of the four datasets: point clouds coulred by RGB full (top), detailed pointcloud of a knot coloured in RGB and by heigth (second and third row) and histogramms for the heigth differences to the best-fit plane (bottom).

Dataset	Number of images	Number of points	Mean point spacing / mm	Mean intensity
A	11830	44279597	0.065	29
B	1919	47258142	0.061	24
C	360	30366709	0.056	63
D	528	56274312	0.046	49

Table 2: Parameters of the 3D models based on the four datasets.

5. Discussion

The possibility to choose the lighting direction afterwards is a major advantage of RTI models over simple images. That way it is not necessary to know exactly which illumination and therefore information are needed at the time of the acquisition. Our case studies show that different lighting directions can amplify the perceptibility of wooden structures. However, detecting a knot in the RTI model is not enough. For a true localisation the detected knots must be geo-referenced in the context of their surroundings, either the local coordinate system of a single timber or the global coordinate system of a whole roof. One approach for this is creating 3D models that could be matched to a 3D BIM model of the whole roof structure. Because of the used camera in our RTI dome, we had to do a calibration beforehand. After that we were able to create visual appealing 3D models. These models have a sufficient geometric quality compared to 3D models based on conventional photogrammetric images. In some cases, the quality was even better, because the LEDs of the RTI dome illuminate details like cracks that are too dark to be reconstructed with the data of the DSLR camera.

We have tested three datasets captured with the RTI dome and compared the results to evaluate the best images and the optimal workflow. Regarding the geometry dataset A showed the best metrics implying to be the superior dataset. However, due to the high number of images, the data processing is very time-consuming. Therefore, using only a subsample of the images like dataset B could be an alternative approach. The geometry has a comparable quality to dataset A and is still even better than dataset D, which is not what one would expect and worth for further investigating.

6. Future Works

In this paper we have presented a portable RTI dome for the documentation and localisation of wooden knots in heritage timbers. We have used different subsamples of the RTI images in a SfM pipeline and show that high-quality 3D models can be created. This opens a potential to register the RTI models to the 3D model. The next step will be the combination of all information in one representation. If a wooden knot is found in one of the RTI images and the position of the RTI model is known in relation to the 3D model, the detection can be projected onto the 3D model. If only single beams are considered this is appropriate for the localisation, but in the context of roof frameworks further steps are necessary. In this case there are multiple wooden beams over a large area. Capturing the whole area with the RTI dome and SfM is too time-consuming and therefore practically impossible. As one option, an additional measurement system with a wider range could be used. A possible system would be a terrestrial laser scanner or a more compact lidar scanner as integrated on modern smartphones. It should be possible to capture the roof framework with a few positions. Subsequently, the 3D models from the RTI images could be referenced to that superordinate model.

Furthermore, it would be reasonable to optimize the construction of our dome as well. The 3D printed parts are cheap in production, but therefore not completely stiff. A deformation of the dome changes the position of the LEDs. If this happens the calibration of the lighting directions is not correct anymore. This should be investigated in further studies and the influence on the quality of the RTI models should be evaluated. If a significant loss in quality can be proven, a stronger dome should be developed.

The workflow from the data acquisition to the RTI model can be optimized as well. The RTI dome is an appropriate tool for image acquisition, but the processing of these images is time consuming, even with software like RelightLab. It is desirable to develop a process that automatically takes the images after the acquisition and calculates the RTI models on the spot. Another reasonable step in this workflow would be a colour calibration of the RTI images. Our experiments show that the colour quality is comparable to conventional camera technique but could be improved. A major advantage of RTI, especially using a dome, are the fully controlled lighting conditions. This way, it should be possible to get a high-quality colour calibration by computing correction parameters for each single image and therefore a more realistic RTI model.

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