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INVESTIGATING CONDENSATION RISKS ON HERITAGE BUILDING SURFACES USING BLINN-PHONG BRDF MODEL AND ATTRIBUTE INFORMATION OF POINT CLOUD DATA

YULIANA[1], MUHAMMAD RAFIF CAHYADI AGUNG[2], MUHAMMAD ARIF RAHMAN[3], MIKTHA FARID AKADRI[4], CAROLA HEIN[5]
[1234]Cluster of Architectural Sciences and Building Technology (ASBT), Department of Architecture, Universitas Indonesia.
[5]Chair of History of Architecture and Urban Planning, Faculty of Architecture and the Built Environment, TU Delft
[123]{yuliana/rafif/arif}@par-lab.com, 0000-0001-5785-2421, 0000-0001-9712-3127, 0009-0005-1897-1221
[4]miktha@ui.ac.id, ORCID: 0000-0002-9772-742X
[5]C.M.Hein@tudelft.nl, ORCID: 0000-0003-0551-5778

Abstract. To date, the preservation techniques of heritage buildings in Indonesia are still limited to physical measurement, most of which are based on manual records. Consequently, lack of accuracy, cost and time consumption often lead to misinterpretation of crucial information during the decision-making process. This part includes physical damage (i.e., mold growth, flaking paint, water leaks), caused by condensation due to high relative humidity. Thanks to the development of advanced laser scanning technology, high-precision point cloud datasets can be obtained to conduct surface performance analysis. Furthermore, this study proposes an integrated computational method for detecting condensation risks in heritage buildings by making use of optical and thermal properties calculated from point cloud data. The proposed method specifically employs Blinn-Phong Bidirectional Reflectance Function (BRDF) model to calculate the distributed reflectance in a material based on the angle of incidence and material reflectance. Along with it, the point cloud measurement is also coupled with FLIR One Pro IR camera and HOBO data logger to analyze the thermal performances of the building surface. Ultimately, this study will provide architects with a better understanding regarding potential risks of condensation in the heritage building surface so that they can perform early detection tasks.

Keywords. Cultural Heritage Building, 3D Scanning, Thermal Properties, Optical Properties, Blinn-Phong BRDF.

1. Introduction

As part of Sustainable Development Goals (SDGs) 11 Target 4, cultural heritage

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buildings play a vital role not only as valuable national assets but also as a symbol of cultural identity. Nonetheless, preserving heritage buildings presents a considerable challenge, particularly in humid tropical regions such as Indonesia, where high moisture contents in the atmosphere may pose significant threats and potentially lead to serious defects such as condensation and rising damp (RICS, 2019). This can be seen in the abandoned "Gudang Timur Batavia" and the renovated "Toko Kompak" (Tifada and Winardi, 2022), where physical cracks on the building surface are clearly visible. Detecting and preventing the effects of condensation early on is vital due to its long-term impact on the building surfaces. Various methods of moisture detection, ranging from Ground Penetrating Radar (Barone and Ferrara, 2018) to 3D laser scanning (Lerones et al., 2016), have been conducted. However, these methods remain great challenges not only on technical considerations regarding dataset processing but also the audience of the existing studies that mostly coming from engineering domain. To respond this issue, this study aims to investigate condensation risks in heritage buildings using 3D scanning and thermal imaging camera. In this case, Blinn-Phong Bidirectional Reflectance Function (BRDF) model (Lafortune and Willems, 1994) is specifically employed to calculate the distributed reflectance in a material based on the angle of incidence and material reflectance. This model is also used to compensate for Phong BRDF (Montes and Urena, 2012) which has similar values between incident and reflectance angles. This model provides relevant approach since Blinn-Phong BRDF has a similar mechanism to the laser beam reflection of Terrestrial Laser Scanning (TLS). In this regard, the direction of reflected laser beams is identical to the vector between radiance and irradiance that calculated in the Blinn-Phong BRDF. This paper is then structured across six sections containing theoretical background, computational processes, case study, simulation results, and concluding remarks.

1.1. 3D SCANNING AND PHOTOGRAMMETRY FOR CULTURAL HERITAGE BUILDINGS

The utilization of 3D scanning tools in reconstructing architectural heritage allows for the preservation of cultural landmarks. This tool offers time efficiency, detailed results, cost-effectiveness, and metadata for further material analysis (Costanzo et al., 2015). Recent advancements involve a combination of 3D scanning with other techniques such as Rocha et al., (2020) use 3D scanning and photogrammetry for parametric smart models of heritage buildings, while Lee and An (2023) investigate high potential HBIM for representing Korean heritage structures. Khalil and Stravoravdis (2019) highlight HBIM's broad applications, including historical data documentation, building issues detection, and performance simulation aspects. This tool further offers precise geometric reproduction and color data that can be used to detect structural damage and energy efficiency assessment (López et al., 2018). Despite its potential development in cultural heritage building contexts, studies regarding the early-phase detection of moisture and condensation risks using 3D scanning technology remains largely unexplored. Thus, this study aims to fill this gap by exploring a computational method to detect condensation risks on building surfaces through reflectance properties.

1.2. CONDENSATION IN BUILDING

Condensation, the transformation of water vapor into liquid, occurs when moist air cools below its dew point temperature upon contact with a cold surface and this may potentially lead to moisture-related risks in heritage buildings. Here, the dew point temperature is calculated using equations 1 (Marcelić and Malarić, 2017), as follows:

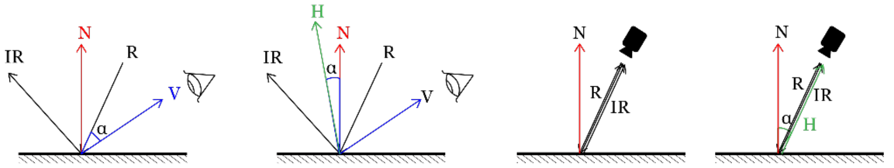
$$T_d = \frac{B1\left[ln\left(\frac{RH}{100}\right)+\frac{A1T}{B1+T}\right]}{A1-ln\left(\frac{RH}{100}\right)-\frac{A1T}{B1+T}} \qquad (1)$$

where:
Td = Dew point temperature (°C)
B1 = 243.04 °C (constant)
A1 = 17.625 °C (constant)
RH = Relative Humidity (%)
T = Room temperature (°C)

There have been several studies attempting to investigate condensation in the historical building such as D'Ambrosio Alfano et al., (2023) who investigate moisture sources using thermographic analysis for reliable measurement. Muradov et al., (2022) also employ microwave systems, photogrammetry, and laser scanning to identify wall moisture contents and albeit with limited surface coverage. However, studies that specifically examine moisture existence and condensation risks through optical properties (i.e., BRDF) of surface materials are rarely found.

1.3. BIDIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION (BRDF)

Understanding the relationship between optical properties stored in point clouds and their impact on building conditions highly corresponds to the principle of reflectance properties from optical observations. In this regard, reflectance properties in remote sensing encompass albedo, emissivity, and BRDF. Albedo measures the proportion of reflected light from a surface, while emissivity gauges an object's effectiveness in emitting energy as thermal radiation. BRDF accounts for the directional properties of reflected light concerning illumination and viewing geometry (Nicodemus et al., 1977). It principally characterizes surface properties based on radiance and irradiance factors.



(a) Phong BRDF Model (General)
(b) Blinn-Phong BRDF Model (General)
(c) Phong BRDF Model (TLS)
(d) Blinn-Phong BRDF Model (TLS)

Figure 1. The difference between Phong and Blinn-Phong BRDF in general concept and TLS (elaborated from Montes and Urena, 2012)

The comparison between the Phong BRDF and Blinn-Phong BRDF model can be seen in Figure 1. Here, Figure 1a and 1b present the general model of BRDF while Figure 1c and 1d are the BRDF model when using the TLS dataset. The basic Phong BRDF model can be calculated using the equation (2) below:

$$F_r(v,r) = kd + ks(v\,.\,r) \qquad (2)$$

Where:
Fr = BRDF Value
v = The vector of the observer's point of view
r = Radiance
kd = Diffuse coefficient
ks = Specular coefficient

The general Blinn-Phong BRDF model has another vector called H, which is the vector between the radiance and the irradiance. Aside from that, the angle of incidence is the angle between the vector H and the vector of the surface normal. The general Blinn-Phong model can be computed based on the following equation (3):

$$F_r\,(n,h) = kd + ks(n\,.\,h) \qquad (3)$$

Where:
Fr = BRDF Value
n = The vector of the observer's point of view
h = Vector between radiance and irradiance
kd = Diffuse coefficient
ks = Specular coefficient

Since this study uses TLS, the laser is transmitted and emitted in the same direction. This can be seen in Figure 1c and 1d. This results in a H vector that is also facing in the same direction. The dot multiplication of vector n and h is described below (Equation 4):

$$n\,.\,h = |n||h|\cos\alpha\,, |n| = 1$$
$$\frac{n\,.h}{|h|} = \cos\alpha\,, |h| = 1$$
$$n\,.\,h = \cos\alpha \qquad (4)$$

Because the magnitude of vector n and h is 1, the Blinn-Phong BRDF Model (Eq. 3) can be transformed into Eq. 5 mentioned below. This study employs Eq.5 since it corresponds to TLS dataset processing.

$$F_r\;(n,h) = kd + k\cos\alpha \qquad (5)$$

Where:

Fr = BRDF Value
n = The vector of the observer's point of view
h = Vector between radiance and irradiance
kd = Diffuse coefficient
ks = Specular coefficient
α = angle between n and h

2. Method

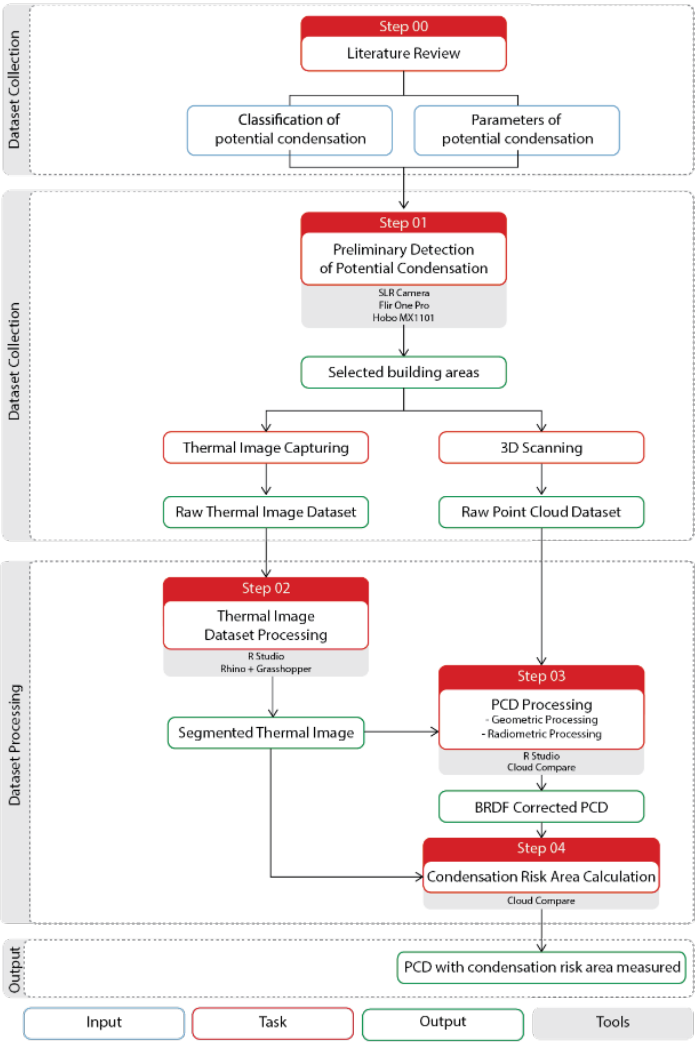


Figure 2. Research Workflow

The study aims to construct a computational method by making use of TLS and environmental monitoring devices to pinpoint and classify areas prone to condensation in building structures. The five-step framework, depicted in Figure 2, begins with a literature review to identify condensation classifications and parameters. Then, preliminary detection of potential condensation areas is conducted using thermal imaging and 3D laser scanning. The processed data is then used to identify condensation risk areas and correlation analysis between surface temperature and BRDF values.

Furthermore, the potential room is determined for further investigation based on proposed classification of potential condensation. In this regard, four types of potential condensation are identified based on physical condition, duration, air temperature, relative humidity, and room conditions. It ranges from potential to high destruction level. Each level then correlates with specific conditions such as dust accumulation, colour change, mold growth, and peeling paint. This classification is referred to ISO 22185-1:2021.

Second, after the potential room is selected, several environmental measurements are carried out. To have a reliable result, this process uses several devices such as Hobo MX1101 for air temperature and humidity, a digital camera for visual signs, and an Infrared (IR) thermal camera (Flir One Pro) for surface temperature data. Furthermore, thermal image datasets and detailed 3D scanning are collected for further analysis. In this regard, thermal image datasets are segmented and aligned with retrieved point cloud data from 3D scanning. The dataset processing of point cloud data involves geometric and radiometric preprocessing based on BRDF.

To ensure the accuracy of point cloud data, geometric preprocessing should be done first. This includes a subsampling and outlier removal process. This step is used not only to reduce the point but also to minimize the computational workload. After the geometric preprocessing, the following step is radiometric preprocessing which consists of normal calculation, intensity correction, and intensity normalization. To conduct the intensity correction and intensity normalization, another attribute information of point cloud is needed namely surface normal (Nx, Ny, Nz). This attribute can be fulfilled by computing the normal vector for each point cloud. Moreover, the intensity correction and intensity normalization are conducted due to various distance of point cloud collected through TLS and this may affect the intensity value of point cloud data.

Furthermore, geometric and radiometric preprocessing can produce corrected point cloud data. Then, to investigate the condensation risk through optical properties, Blinn-Phong BRDF model is calculated. To do so, thermal properties and optical properties are needed. Thermal properties consist of intensity correction and RGB while optical properties include XYZ data and surface normal dataset.

The final phase of the proposed method in this study involves calculating areas susceptible to condensation risk using the processed Blinn-Phong BRDF point cloud dataset and comparing it with segmented thermal images. This part is done using Cloud Compare tool. The dataset is cropped by surface temperature ranges, to identify areas of building component that contains a high potential condensation risk in square meters.

In summary, this study offers a systematic computational approach utilising various tools to identify, classify, and measure the condensation risk. The result is expected to provide a broad understanding of potential moisture damage in the heritage building surface so that early prevention can be done.

2.1. CASE STUDIES

Figure 3. Cut Meutia Mosque

The selected case study is Cut Meutia Mosque or known as NV De Bauploeg building built in 1912. This building consists of 2 floors (Figure 3), indicating that this building contains a high ceiling. The distance between the 1st floor and the 2nd floor is 3.5 meters, while from the 2nd floor to the ceiling is 11.5 meters. The Cut Meutia Mosque is located in Cikini, Central Jakarta, Indonesia. This building is used as prayer hall for Muslim since 1987.

3. Result

Figure 4 shows environmental measurement of Cut Meutia Mosque, to determine selected rooms for further investigation. The horizontal axis shows the timestep during the data recording around the Mosque, while the vertical axis shows the temperature values. Based on Figure 4, the highest humidity can be spotted in A6, A2, B1 and B2 rooms, caused by the peeling paint and several wall damage in the rooms.

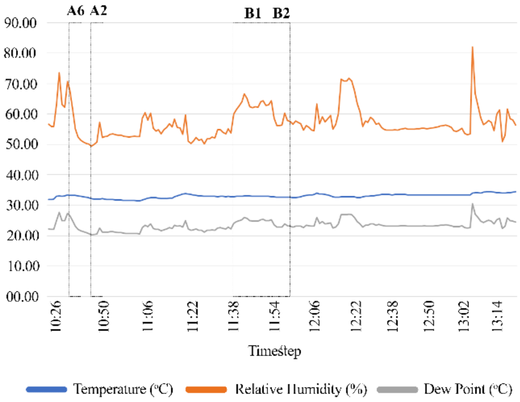


Figure 4. Environmental parameters evaluation in Cut Meutia Mosque

Furthermore, thermal image of the selected room is captured in the same day as the environmental measurements. Afterwards, thermal image is segmented, resulting in the widest segmented area around 27.5 - 28 °C for each room, except for B1 within the range of 27 - 27.5 °C. Then, segmented thermal image areas with a temperature range of 27.5 - 28 °C for A2, A6 and B2, 27 - 27.5 for B1 are selected for further analysis, namely PCD and thermal images alignment.

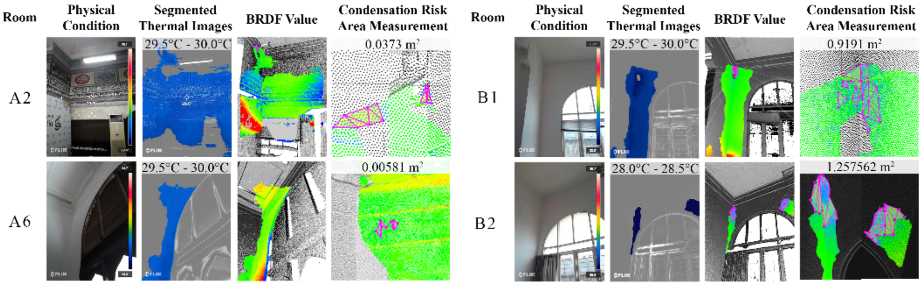


Figure 5. Condensation risk area based on surface temperature and BRDF

The result of Blinn-Phong BRDF shows that the darker the colour ranges (Figure 5) the lower the BRDF value, which then represents the existence of moisture substance on the surface of the material. Furthermore, thermal image and Blinn-Phong BRDF alignment provides an indication of condensation risk in heritage buildings. For example, A2 has 0.0375 m^2 of condensation risk area, A6 has 0.00581 m^2, B1 has 0.9191 m^2 and lastly B2 has 1.257562 m^2 condensation risk areas capturing.

4. Discussion

The findings of this study highlight the potential of our proposed approach in identifying condensation risk in heritage buildings based on BRDF values and surface temperatures. By integrating 3D laser scanning and thermal imaging, this method showcases potential applications of detecting moisture and condensation risks. This method provides architects and building conservators with a comprehensive workflow to prevent leaks and damage in heritage structures.

To some extent, this method presents different results regarding surface temperature when taking different angles of view using a thermal imaging camera, especially for capturing thermal images located on high ceiling. Thus, this study employs 3D point cloud data to compensate this issue in order to enable the calculation of condensation risk areas in a three-dimensional environment. While there have been several existing studies conducted to detect moisture conditions in the heritage building context, they often face similar challenges in indoor settings. This can be seen in Dafico et al., (2022) who compare detection tools like surface moisture meters, Wu (2020) who combine thermal cameras with RFID to detect moisture based on signal stability, and Nguyen et al., (2019) who reveal the condensation growth mechanism through macro-photography techniques but is limited to smaller scales.

Nevertheless, some studies are closely related to our proposed method. For example, Dlesk et al., (2022) conduct an experiment with photogrammetric processes using thermal images, aiming to overcome negative factors and integrate them with RGB images. Costanzo et al. (2015) demonstrate the potential of combining thermal imaging and terrestrial laser scanning to detect anomalies and improve knowledge regarding the health of masonry buildings. In general, this study provides a novel method not only to detect the building damages but also to identify specific areas of the condensation risk.

5. Conclusion

This study specifically investigates condensation risks in heritage building surfaces by using point cloud data incorporated with thermal imaging. Specifically, the proposed method employs Blinn Pong BRDF model to identify the moisture level of surface dataset. This study has confirmed a strong correlation between BRDF values and surface temperature when detecting condensation risks in heritage building surfaces. In this regard, low BRDF can indicate specular reflection from the surface dataset leading to the identification of the moisture level of the surface material.

Ultimately, this study enables architects or building conservators to evaluate the microclimatic impact on existing heritage building surfaces at an early stage, before encountering physical damage regarding condensation risks.

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