A Computer Vision-Based Long-term Monitoring Framework for Biobased Materials

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In this paper, we describe an automated remote monitoring system to uncover the impact of environmental phenomena on 3D printed bio-polymers behaviour and lifespan. The novel fully automated in-service framework allows for long-term monitoring with a wide range of wired and optical sensors and to correlate and analyse the gathered data. A focus is set on non-invasive measurements with Computer Vision technology. Here we introduce a computational image pipeline that allows for automated analysis and feedback on monitored bio-composite samples and assemblies. The framework is easily deployable, cloud-based, and accessible remotely. We evaluate the function and reliability of the framework in two design cases indoors and outdoors and gather insight for future practice with bio-based materials on both design and in-service levels.

Keywords: *Automated Monitoring, 3D Printing, Biopolymer, Material Behaviour, Weathering.*

INTRODUCTION

The AEC industry is in a transition from being based in non-renewable materials of the geosphere to the renewable resources of the biosphere. Bio-composites emerge as a promising material class. They are however characterized by strong behaviours in response to environmental factors such as humidity and temperature and have a shorter life span (Thomsen and Tamke, 2022). Current industrial practices aim to minimise material behaviours and to achieve homogenous and ideally everlasting materials. These characteristics can often only be accomplished in wasteful, energy intensive and often toxic processes. An alternative route is to use the materials in a raw state and integrate the behaviours and interaction of materials with the environment into our practices of design, fabrication, inhabitation, maintenance, disassembly, reuse, and recycling.

How to establish the knowledge, tools, and protocols for this emerging practice with materials with inherently shorter lifespans is the subject of the ERC funded project Eco-metabolistic Architecture (EMA). One investigated concept is that of circular construction, where biobased building elements are not only designed according to their behaviours, but their behaviour in the built construction is as well monitored in situ and they are replaced or repaired, when the observed performance is no longer sufficient. Monitoring of elements must therefore take place for the detection of material behaviours and for the observation of it in the service life. While the subject of the monitoring framework in our experiments are bio-based materials, it is not limited to it and can be used to observe the long-term behaviour of other materials.

Monitoring the built environment

Monitoring is an established practice in the design and maintenance of the build environment: sensors are used in buildings to improve building efficiency and environmental comfort (Metallidou et al., 2020) as well as in heritage building for environmental monitoring to ensure preservation of museum artefacts (Klein et al., 2017). Monitoring data is used for predictive maintenance (Cheng et al., 2020), control of structural health, as in concrete columns in parts of the world with higher seismic activities (Glisic, 2007) or for timber bridges where degradation is tracked through in situ monitoring (Tannert et al., 2011). Sensors can be embedded in the material to gain local (micro level) data for e.g. monitoring the success of concrete curing (Cabezas et al., 2018) or for feedback loops to design with Phase Changing Materials (Faircloth et al., 2018b). Sensors might collect data automatically and record e.g. measured wood moisture content in timber bridges and facades on data loggers, which are queried and maintained during inspections (Brischke et al., 2008), or they conduct remote sensing, meaning that they work autonomously, and send data automatically to the cloud (Faircloth et al., 2018b) and maintain it via remote access.

Computer Vision provides a mean to minimise the cost and efforts to plan, setup, and maintain above described complex wired sensor networks (Faircloth et al., 2018a). They minimize the impact of the sensors on the material behaviour and allow the observation of interaction between environmental forces and the overall structure on meso level, e.g. for automated monitoring of tunnel deformation. (Qiu et al., 2018)

Monitoring the behaviour of materials over time

Monitoring the environmental impact (weathering) on building materials is key in the development and certification of them. They are commonly tested via two protocols: Accelerated weathering which is a weeks-long process, taking place in climate-controlled chambers with programmed weather cycles of a limited set of factors, such as UV, moisture and temperature, and natural weathering where materials are monitored over periods of half to many years. Here measurements are correlated with local environmental conditions such as solar radiation, temperature and rainfall (Sandak et al., 2019).

While accelerated weathering is only performed on small samples, Natural weathering can be performed on large-scale building elements as well. In the latter samples are typically placed on a rig with different orientations and measurements are gathered by an expert to test surface quality, mechanical and chemical properties (Sandak et al., 2015). In both accelerated and natural weathering procedures, measurements are usually not taken via automated processes, but manually in intervals by experts and analysed in a lab. While both methods are valid, it is nearly impossible to deduce real world behaviour from accelerated weathering alone (Kržišnik et al., 2018).

Monitoring composed biomaterials

Not much long-term monitoring has taken place with composed biomaterials – the focus of our research. Their composition is based on a water medium, a binder and reinforcing cellulose fibres (Rech et al., 2022). Bio-composite materials for additive manufacturing have a slurry viscosity when mixed and can be graded by varying ingredients which gives the material different properties (Chiujdea and Nicholas, 2020); (Dritsas et al., 2019). After fabrication, the prints undergo a curing stage. Rossi et al. (2022) developed a monitoring framework for tracking the curing phase which integrates moisture sensors, thermal and RGB cameras, motion capture markers and ambient sensors. Data is gathered at a set time interval through timestamp tool and uploaded on a cloud-based storage. Bio-composites can be dead or alive, as in the case of mycelium composite panels tracking for durability, efficiency of manufacturing methods, growth and contamination which span over 7.5 months (Houette et al., 2020).

Weathering of cellulose based polymers

In our research on cellulose-based composites, we observed that the lifespan of the composites outdoors can span from few weeks to a few months. To evaluate this more accurately, we constructed in 2021 a monitoring rig to expose 3D printed diamond shaped panels to three different outdoor conditions: south and north facing and sheltered. We exposed three sets of nine panels, and we tested three toolpath geometries with varying density for the three recipes. The panels were tracked for six months. During this time, a researcher took photos, 3D scans and measurements of the samples. Our results illustrated that rainfall has the highest impact on their deterioration of all environmental factors.

While these results could be deducted from manual observation, the process is not only labour-intensive but also susceptible to human error. A more sophisticated system is required. To collect data that can feedback into architectural design and maintenance processes, we find that it is necessary to develop a remote multi sensor framework, which collects and analyses data in a consistent and automatic way, resulting in parameters which represent state and change of materials in a quantitative and reproducible way.

METHOD

The framework for sensing and detection of the 3D printed parts' behaviour can be divided into two categories: 1. Environmental sensing and 2. Computer vision. The framework needs to be easily deployable by a non-professional user, accessible remotely, automated for scheduled observations, and weather proof. The monitoring in this paper takes place indoor and with an outdoor setup via a rig. The rig carries all the sensors for monitoring as well as all biopolymer samples (figure 1).

Figure 1
First iteration of the outdoor monitoring rig in Copenhagen, facing southwest positioned on a height of ca. 3 meters. To the right the box with sensors and local minicomputer. On the cantilevered arm a 4K camera.

Remote Sensing

Remote data collection requires devices which are mobile, accessible, and have wireless internet connection. They might run via local power or PV cells. In our experiments, we used the single-board computer Raspberry Pi with a custom designed and manufactured electronic shield for the sensors. Raspberry Pi has many features which met our conditions for remote sensing such as the small size, accessibility, and IOT based applications. A main concern is the need to control the board remotely and securely. This requires to our experience often the circumvention of local security protocols which we achieve through a Virtual Network Computing (VNC) server. Secondly, the applications need to run automatically on fixed intervals which is done via Crontab to schedule iterative monitoring runs. Finally, we need to monitor the monitoring, which is done by Cronitor, a general-purpose monitoring tool to track the availability and performance of background jobs with alerting method for possible disruption in the data flow.

Environmental Sensing

While weather networks provide information on urban climate, we find that we need to track climate for our purpose on Local and Microclimate scale. Local climate data is collected via a weather station installed on site and the microclimate on the level of the measuring rig is gathered via sensors installed adjacent to the bio-polymer samples. The weather station tracks temperature, dew point, humidity, wind (direction, speed, gust), pressure, precipitation (rate and accumulation), UV, and Solar radiation and the sensor box tracks local temperature, humidity, Infrared light, and lux. In total 19 data points which are result of direct and indirect sensing are collected. The sensed data is collected in intervals of 5 min and is sent for storage and analysis to InfluxDB, an open-source cloud-based time series database.

Non-invasive monitoring

We use a non-invasive monitoring technique to ease collection and avoid interaction between the samples and the electronic parts, which would influence the measured data. We assess the samples therefore visually via an IP camera with IP66 protection, which sends images to the cloud.

VISION BASED MONITORING

Computer Vision (CV) based monitoring adds the capability of tracking a wide variety of quality characteristics, such as dimensional data, geometry, and defect patterns (Megahed et al., 2011). By and large, CV systems share a common procedure that includes image acquisition, image pre-processing, feature extraction (Yan et al., 2015), and analysis. The image acquisition in our experiments is synchronized with sensed data collection through Raspberry Pi, and all the data are related via timestamp. To detect temporary and permanent changes in the samples the images from the camera need to pass an image pipeline, where faulty images are removed and processed through image stabilization, object isolation, and analysis (figure 2).

Image stabilization

In the first step images are validated. Here blurred images and photos taken during challenging weather condition (e.g. rain and snow) are removed ("changedetection.net," n.d.). Then, the raw images are undistorted using the camera matrix and distortion coefficient based on a checkerboard calibration in OpenCV. After calibration and quality control the images are aligned and ready for object detection and analysis.

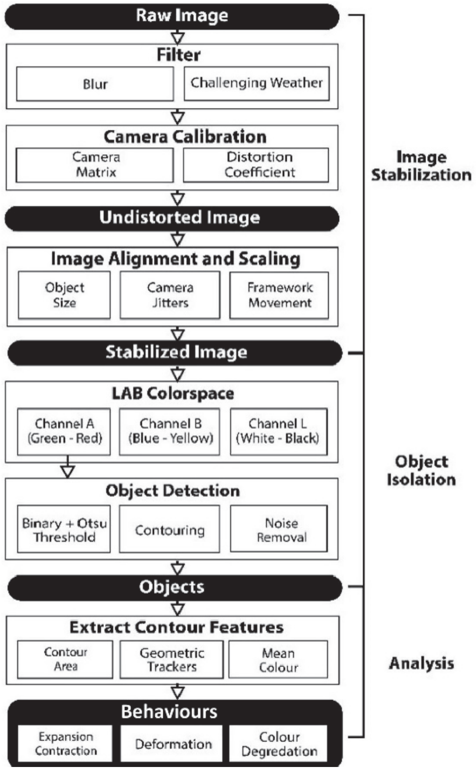


Figure 2
Image pipeline from the image creation to the feedback into a design system.

Object isolation and analysis

All verified images undergo a background subtraction process in which objects of interest are detected and their features e.g., contour area, centre of contour, among others are extracted. To observe the objects' behaviour, their geometry needs to be detected and tracked over time. While the use of physical trackers on objects is a common method for indoor monitoring (Rossi et al. 2022), the limited number of trackers on a complex geometry, their susceptibility to weathering and their influence on the-samples limits their use.

We use instead a CV approach for a geometrical analysis of the samples and maintain the consistency of the monitoring framework in the long run. To extract geometrical characteristics, we used the mask of the objects to achieve the contours and contour features. Next, we detect the expansion and contraction of the parts by means of the contour area difference over time. The changes in direction of the parts in relation to the fixtures are tracked through the angle between the bounding rectangle and minimum area bounding rectangle and, in the end, the geometry deformation is tracked using the centre of contours, farthest points in 4 directions, convex hull points, and convexity defects.

CASE STUDIES

We deployed the framework in two case studies, one indoor and one outdoor. The latter is done in two iterations to improve the accuracy of the framework.

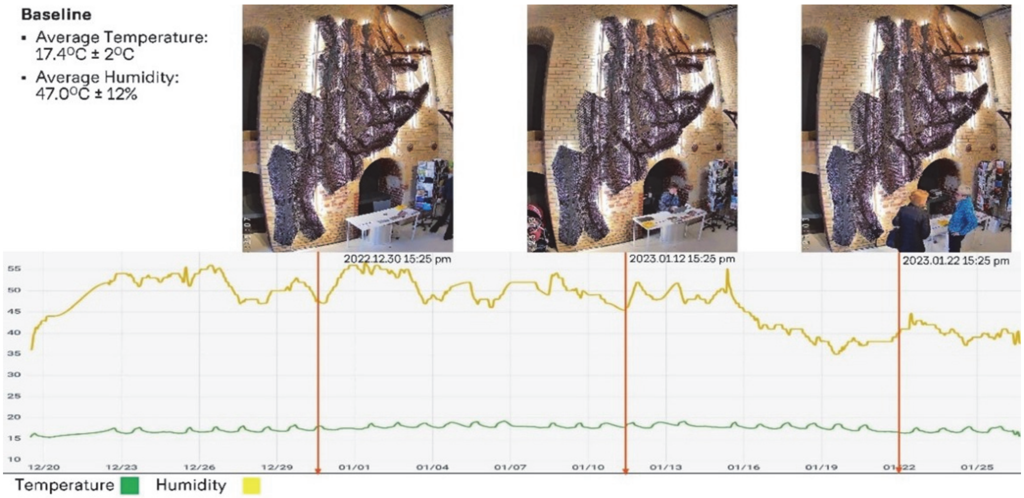
Indoor monitoring

In the first experiment, we installed an in-situ monitoring during the Living Prototypes exhibition in the Aedes Gallery in Berlin (Figure 3). The objective was to test the reliability, deployability and remote sensing techniques of the framework by tracking over the course of 35 days "Radicant", a wall piece made of 26 3D-printed biopolymer panels (Nicholas et al., 2023). The aim of this experiment was the detection and analysis of the overall assembled surface rather than individual panels. The sensors box and the camera were installed by a nonexpert user. Given the constraints in relation to the security protocols for a remote connection, consistency of data transfer success, limited memory storage, poor internet connection, and visitors interference with the installed devices, we had to adapt our processing pipeline to tackle each issue.

The secure remote connection worked flawless and the Cronitor alerting system helped to maintain the data flow consistency by informing the exhibition coordinator to interfere, when necessary, as in the event of accidental power outages. Cronitor was also able to track low performance rate during opening hours due to poor internet connection, which was resolved by saving data locally, however, the limited memory storage reduced the efficiency of the board. To tackle this an algorithm was developed that checks the local drive for possible failure and uploads the data to OneDrive. Lastly, accidental camera movement was another issue we encountered which was solved using feature detection and homography methods.

Our results demonstrated that the remote sensing framework worked successfully over 35 days, and remote access helped to update the

Figure 3
Living Prototypes exhibition: indoor monitoring framework



algorithms for data collection and analysis. The collected data show that the overall assembly had a negligible amount of shrinkage over the tracked period, which we can correlate to the observed stable temperature and humidity conditions in the exhibition space.

Outdoor Monitoring

In the second experiment, we exposed six 3D printed samples on a south-west facing wooden frame which carries an aluminium mount for the camera. The monitoring rig faces south with 26 degrees angle toward west (figure 4) and it is exposed to direct sunlight, rain, and other atmospheric conditions that would influence the 3D printed parts. The experiment takes place in Copenhagen from January to March. The aim of this experiment was to develop methods for remote computer vision-based monitoring for an outdoor environment and to track individually the behaviour of the exposed samples. Three out of the six samples are 3D printed using a recipe based on xanthan gum binder (Rech et al., 2022), whereas the other three samples are fabricated using a recipe based on collagen binder (Nicholas et al., 2023). One sample of each recipe was coated with the collagen binder. The wooden frame and the aluminium camera mount moved in the wind, which required image alignment for analysis. Because of the similarity in colour of some samples with the wooden frame and the grey building facade, it was not possible to distinguish the sample from background accurately in different lighting conditions during the day.

In the second iteration of the outdoor monitoring framework, we tackled these issues and installed a green screen (figure 5). The uniform colour opposing the 3D-printed objects allowed us to use a robust colour filter algorithm, so that each sample was detected accurately.

We resolved the problem of camera jitter with the help of Aruco markers on the framework. They have robust detection methods and help in aligning the images accurately, as they become fixed features in the homography techniques. The known print size of the markers allows to determine the size of the objects reliably.

We were able to track the reactive behaviour of the samples to weathering as shown in figure 6. They have a periodically temporary change. Moisture

Figure 4
Location of the Outdoor Monitoring Framework

Figure 5
Second iteration of the outdoor monitoring framework with green screen

absorption from rain and humidity leads to expansion, while evaporation caused by solar radiation and high temperatures lead to contraction. The collected data showed that the collagen-based recipe has a stronger behaviour, where it transitions from a brittle condition to a flexible one as it absorbs moisture, and a reversed conditions as it dries. The xanthan gum-based recipe has also hygroscopic behaviour, in comparison it is though more stable.

The quantification of the contours showed that the 3D printed panels with the Xanthan Gum binder have an average expansion of 3%, while the samples based on the collagen binder have an expansion of 11%. However the experiments were conducted during a cold and wet winter, and we expect a different behaviour in the warm months.

EVALUATION

We developed our monitoring framework and tested it in two case studies. From a monitoring workflow perspective, we proved that our setup could adapt to given site conditions, with remote access for professional users and possibility for non-professional users for local intervention.

For the outdoor case study, the implementation of an automated monitoring framework which incorporates image capture and processing, proved to be vital in our understanding of material behaviour in unstable environmental conditions. The monitoring framework allowed us to correlate precisely the data from sample behaviour and environmental data and deduct time and cause of the detected changes. This was difficult to achieve in our previous weathering experiments based on manual measurements. Furthermore, as in the indoor case study, remote access helped to adjust and improve our workflow and software code constantly.

The outdoor case study is season dependent, hence for the winter season we observed in the panels a high responsiveness towards humidity and rainfall. Object detection was the tool of choice to track and quantify the swelling of the samples based on moisture intake. We aim to continue this experiment in summer to further develop the algorithm and extend the analysis from geometry change to e.g., the observation of colour change caused by UV radiation.

From a material perspective, our data shows that the 3D printed bio-composites are steadier in an indoor environment with stable humidity and temperature. In an outdoor environment we find that some panels deteriorate quite fast and fail. The remaining panels showed a strong reaction to environmental conditions, where we can quantify the rhythmical swelling and contraction of the panels in response to sunny and rainy phases in the monitoring period of 3 month. Through observation and numeric analysis, we could as well understand how the design, printing pattern and fixture of the panels influence their behaviour (figure 7).

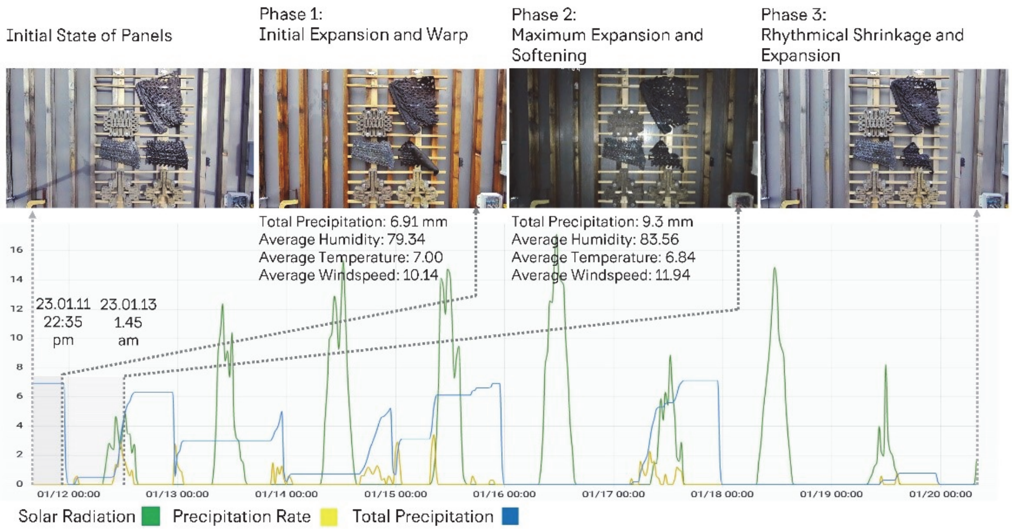


Figure 6
Outdoor monitoring framework

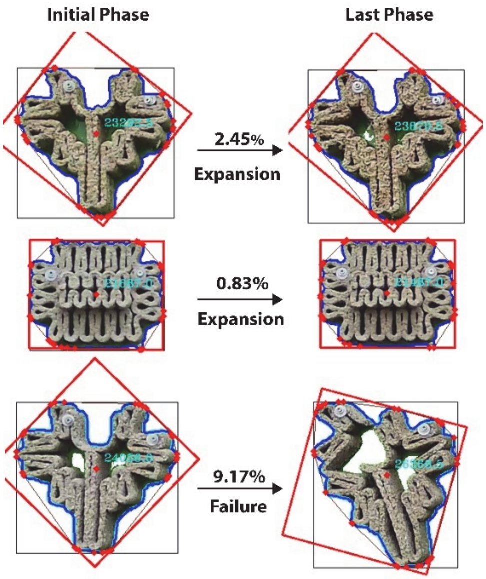


Figure 7 Geometric analysis of the samples' behaviour overtime

General constraints

We find that our image-based approach confirms general limitations of CV in outdoor environments. The changing lighting condition, glares, and shadows on the parts influence the object isolation process. Images taken at night and the influence of challenging weather make it difficult to establish a uniform data collection for analysis. In addition to that the data collected by the camera is influenced by the camera angle and resolution. The swelling of a sample is for instance more pronounced in images that show an object from an angle, than in a planar view.

ARCHITECTURAL IMPACT

The developed monitoring framework can be understood as a first step towards new continuous construction systems in architecture. The demonstrated adaptability of our monitoring framework allows it to scale up and be used for automated monitoring of bio-based materials and other materials for design and maintenance purposes.

The ability to observe visual changes on the level of an element or an assembly can be used to monitor the state of elements and assemblies and trigger maintenance and repair to ensure a healthy service life. For this we plan to incorporate the monitoring framework within an in-situ outdoor structure to track an assembly of bio-composite elements. In this case, we can generate perspectives of continual construction for bio-based composite materials, informed by the monitoring framework.

The gathered data on the behaviour of material in relation to outdoor climates, provides us as well with a numeric base to drive the design of materials for their behaviour over time. Here we can design bio-composite panels in line with their understood outdoor behaviour and design them e.g., in a way that their inevitable failure takes place in a distinct way. The monitoring framework can here again be used to observe and improve the panel design over time.

CONCLUSION

In this paper, we present an in-service monitoring framework for cellulose-based composite materials. We have developed a methodology for automatically tracking bio-composite panels based on environmental sensing and computer vision. The monitoring framework is based on non-invasive sensing methods and can collect and correlate data from multiple sensor types, such as simple One-Wire sensors, weather stations and IP-Cameras. It can be accessed remotely, enabling continuous development and can be adapted and scaled up to local conditions. It is reliable and simple enough to be deployed by non-expert users. We evaluated our methods in two case studies, an in-situ indoor monitoring experiment and an observation rig for outdoor monitoring. The image capture and analysis pipeline help us understand material behaviour in both conditions.

Future development will be made to test colour degradation and volumetric change as well, adapting our current outdoor monitoring framework to an in-situ structure where we can look at assembled structures and enable practices of continual construction through strategies of maintenance and repair.

AUTHOR CONTRIBUTION

The manuscript was written with the contribution of all authors. All authors have approved the final version of the manuscript. Tamke, M., project conceptualization, funding acquisition, methodology, writing – original draft, reviewing and editing, installation, supervision, Akbari,S., methodology, technical implementation, production, installation, writing – original draft, reviewing and editing, Chiujdea, R., methodology, writing – original draft, reviewing and editing, Nicholas, P., project conceptualization, methodology, design concept, , supervision, writing – review and editing, Ramsgaard Thomsen, M. project conceptualization, methodology, writing – review and editing, lab infrastructure, supervision, funding acquisition.

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