In-Situ Ultrasonic Monitoring for Process Monitoring of Digital Light Process 3D Printing

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ABSTRACT

Digital Light Processing (DLP) 3D printing is a widely used vat photopolymerization (VPP) technique known for its ability to produce intricate geometries with a broad range of mechanical properties. However, ensuring consistent, defect-free parts remains challenging, primarily due to shrinkage, partial curing, and uneven exposure. In this work, an in-situ ultrasonic monitoring system is introduced which continually assesses each newly formed layer in real-time. By analyzing how ultrasonic waves travel through each layer, internal flaws down to 0.249 mm^2 were reliably identified, and dimensional accuracy of approximately 0.2 mm was achieved. Identifying defects precisely when they emerge allows immediate corrective actions, significantly reducing material waste and post-processing efforts. This approach provides a promising solution for enhanced reliability and efficiency of DLP manufacturing, particularly in fields such as biomedical engineering and microfluidics, where precision and material integrity are critical.

INTRODUCTION

Additive Manufacturing (AM) is widely employed across various industries such as automotive, biomedical, and aerospace because it allows for the production of highly complex geometries, reduces material waste, and shortens process times [1], [2], [3]. Among the fastest-growing and most commercially viable 3D printing approaches is Digital Light Processing (DLP), which is classified as a vat-based photopolymerization (VPP) process. DLP stands out thanks to its capacity for producing finely detailed parts at high resolution through the selective curing of liquid resin using a projected light mask [1], [4], [5], [6]. DLP 3D printing has found application in a range of impressive, cutting-edge fields including personalized biomedical implants [7], drug-delivery systems [8], and even soft robotics and flexible electronics [9] where extremely precise layer-by-layer fabrication is essential [2], [10]. Despite its many advantages, DLP still encounters challenges such as polymerization-induced shrinkage [6], [11], under- or overcuring [12], [13], and weak interlayer bonds [14], which limit its suitability for high-performance applications. These issues mainly arise from unoptimized printing parameters, including light exposure intensity [5], exposure duration, uneven resin composition, and the mechanical act of separating each newly cured layer from the vat [15]. In certain setups, the repeated peeling action in bottom-up DLP can worsen these problems, causing residual stresses or micro-cracks that reduce the mechanical performance of the finished part [14]. Consequently, creating a DLP platform with refined printing parameters is crucial for ensuring parts have the necessary properties [16], [17]. Therefore, optimizing DLP printing parameters is not straightforward without a clear picture of the dynamic photopolymerization that occurs during the build.

Traditional additive manufacturing quality assurance predominantly relies on ex-situ inspection techniques, which involve post-fabrication testing [18]. X-ray computed tomography (CT) provides nondestructive volumetric assessment of internal defects, dimensional accuracy, porosity distribution, and surface topology [19]. Complementary to CT, destructive mechanical characterization such as uniaxial tensile and compression tests quantifies ultimate strength, elastic modulus, and failure mechanisms. Implementing these methods requires part removal and often sample destruction, resulting in production downtime and material waste. Furthermore, correlating CT and mechanical results with process parameters like resin formulation, layer thickness, exposure dose demands multiple print–inspect cycles, extending development timelines. In low-volume, high-value applications, delayed detection of concealed flaws can incur significant financial and temporal penalties.

To address these limitations, real-time in-situ monitoring techniques have been introduced for vat photopolymerization [4], [10]. Infrared thermography, optical coherence tomography (OCT), and ultrasonic phased-array sensors have demonstrated effectiveness in metal AM and FDM by detecting thermal gradients, layer delamination, and nascent defects [20], [21], [22]. However, DLP resins exhibit high optical scattering and absorption, while recoating and peel motions introduce mechanical disturbances that can misalign sensors [23]. Recent innovations integrate nonintrusive, layer-by-layer diagnostic tools specifically designed for vat processes [24]. For instance, Higgins et al. coupled an atomic-force microscope (AFM) with a DLP platform to map nanomechanical strain induced by polymerization [25], and Brown et al. utilized a nanocylinder AFM tip to quantify local cure kinetics and viscosity dynamics at sub-micrometer, sub-millisecond resolution [26]. These in-situ approaches enable immediate adjustments to exposure dosage and peel speed minimizing scrap rates and enhancing part fidelity without interrupting production.

Among the tools available for in-situ DLP observation, ultrasonic testing (UT) stands out as one of the most promising [4], [29], [30], [31]. Unlike numerous optical or radiation-based methods, ultrasonic waves can penetrate through the surface to uncover hidden flaws like voids, partial polymerization, or delamination—issues that purely optical methods might miss [10]. Since UT can go deeper than the surface, it offers a viable solution for real-time DLP monitoring, even when the resin is opaque [14].

In this paper, we present a UT real-time process monitoring framework specifically adapted to DLP 3D printing. By positioning and moving a 5 MHz ultrasonic transducer near the resin vat, we allow for (1) continual signal capture to track layer geometry and curing progression, (2) real-time recognition of internal flaws or abnormal curing behavior. Leveraging these correlations, we show how real-time ultrasonic information can drive a “digital twin” of the object being printed, enabling predictions about final part performance and paving the way for adaptive control. Ultimately, our work underscores how real-time ultrasonic defect detection can boost uniformity, functionality, and broader implementation of DLP for top-tier applications.

RESULTS AND DISCUSSION

Recent efforts in additive manufacturing (AM) have increasingly focused on real-time process monitoring, using sensors that can detect internal flaws or changes in material properties as each layer forms. Building on these principles, this study employs a 5 MHz ultrasonic transducer for continuous in-situ monitoring of a top-down Digital Light Processing (DLP) system. As shown in Figure 1a, the transducer is positioned adjacent to the resin vat and measures initial/backwall echoes through the uncured resin, thereby mapping the geometry of each newly cured layer.

As shown in Figure 1b, this approach enabled real-time insight into whether each layer met its target thickness and whether any unexpected thickness variations arose. Using ultrasound data, we were able to make a digital twin of printed data. Overall, this framework allowed us to monitor four primary aspects: (1) Dimensional Accuracy, confirming that each layer matched its intended thickness before the next layer began.

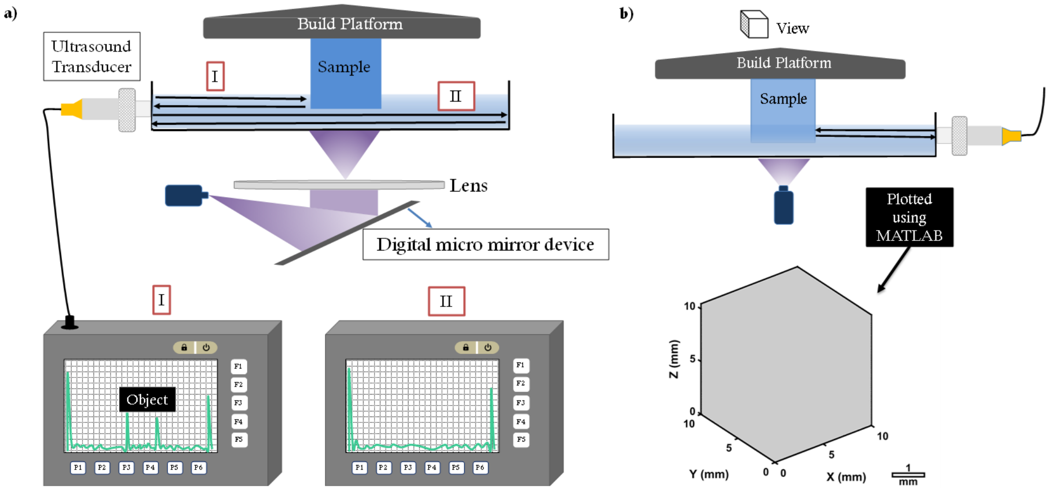

Figure 1. Approach for UT-based in-situ DLP monitoring.

Ultrasonic testing fundamentally involves axial and lateral resolution, which define how finely features can be differentiated along the depth (wave path across the vat) and across the beam width, respectively [32], [33]. As illustrated in Figure 2a, the axial resolution (R_{axial}) is often approximated by:

$$R_{Axial} = \frac{c.n}{2.f} \tag{1}$$

where c is the speed of sound in the medium, n is the number of cycles per emitted pulse, and f is the transducer frequency [34]. This yields a calculated axial resolution on the order of a few hundred micrometers. Meanwhile, the lateral resolution ($R_{lateral}$) dominated by beam geometry, can be approximated in the far field by:

$$R_{lateral} = \frac{1.02.c.F}{f.D} \tag{2}$$

where D is the transducer aperture, F is the focal depth, and 1.02 is a factor for the –6 dB beam diameter in a circular aperture [33]. Given a wavelength λ=c/f, an aperture D=6.35 mm, and a calculated focal depth $F \approx \frac{D^2}{4\lambda} \approx 34.99\ mm$, the lateral resolution is similarly on the order of tenths of a millimeter.

To verify these theoretical estimates experimentally, we printed pairs of small cubes at lateral spacings from 0.6 mm to 2 mm. For each spacing, we repeated the test several times, deriving a detection probability—the fraction of trials in which the ultrasonic echoes unequivocally distinguished two separate reflectors rather than merging into one signal. As shown later in Figure 2b for lateral spacing, and Figure 2c for axial layer increments, detection probability remained low near or below the computed thresholds but rose above 90% once the gaps exceeded the predicted resolution. These outcomes confirm that the beam geometry and pulse length effectively set the limit on minimal feature size detection in our resin-based environment, aligning well with established ultrasonic theory. Using the part thickness, and ToF, velocity of sound in any layer can be determined in this method.

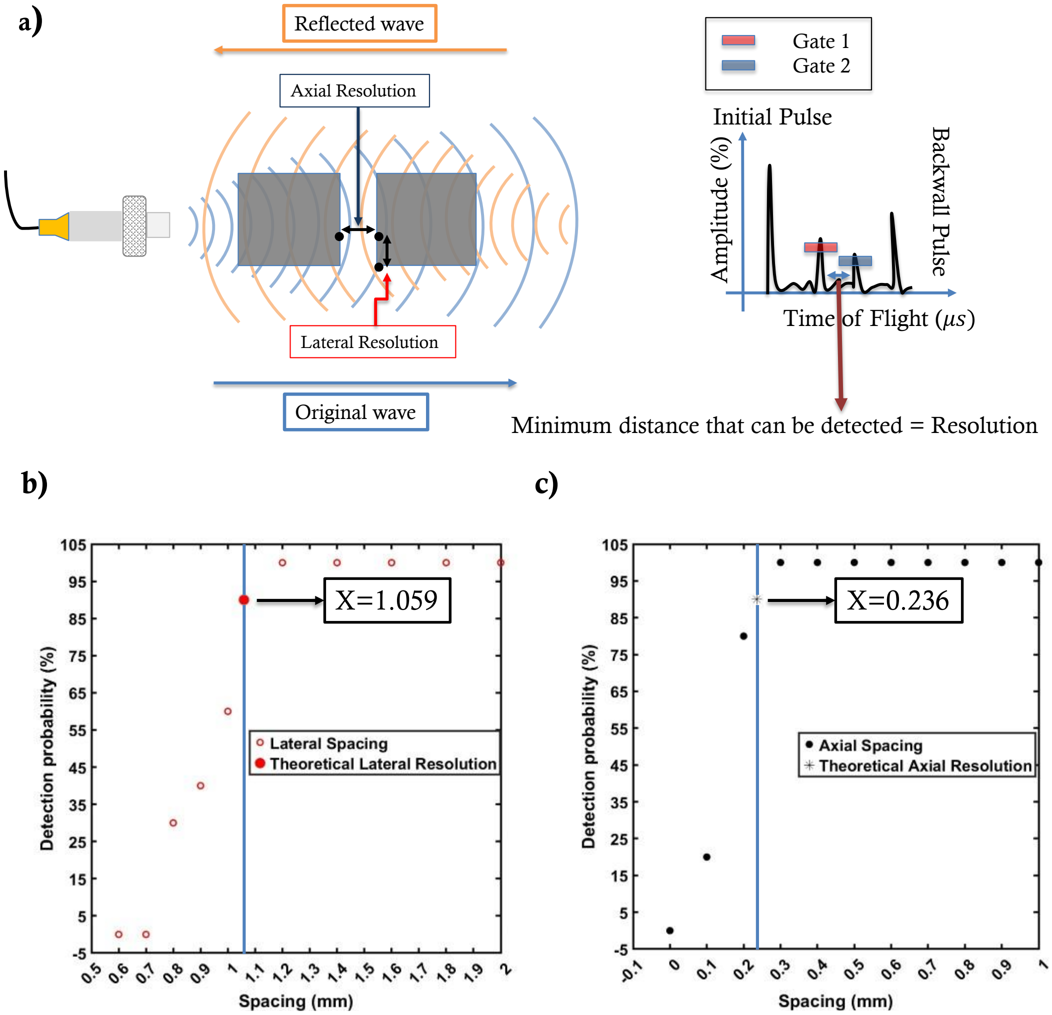

Figure 2. Fundamental of Spatial Resolution, and Detection probability based on ultrasonic resolution.

To further illustrate real-time defect detection, a rectangular void (~3 mm wide) was deliberately inserted into the 10 mm cubical print so that it spanned several build layers. Figure 3a shows the CAD-based model of this hole cutting through the cube. As soon as the DLP platform reached the layer containing the void, the ultrasound B-scan registered a clear secondary echo at the void's top surface, instantly flagging the internal flaw. These anomalous echoes were then stacked, layer by layer, to reconstruct a full 3D digital twin of the printed object, as presented in Figure 4b. In that panel, the greyscale volume shows a well-defined low-signal region corresponding exactly to the designed void, confirming that our ultrasound approach not only flags defects the moment they form but also accurately maps their geometry in real time. By capturing such internal discontinuities as soon as they arise, this method offers powerful, layer-by-layer quality assurance for high-value DLP applications.

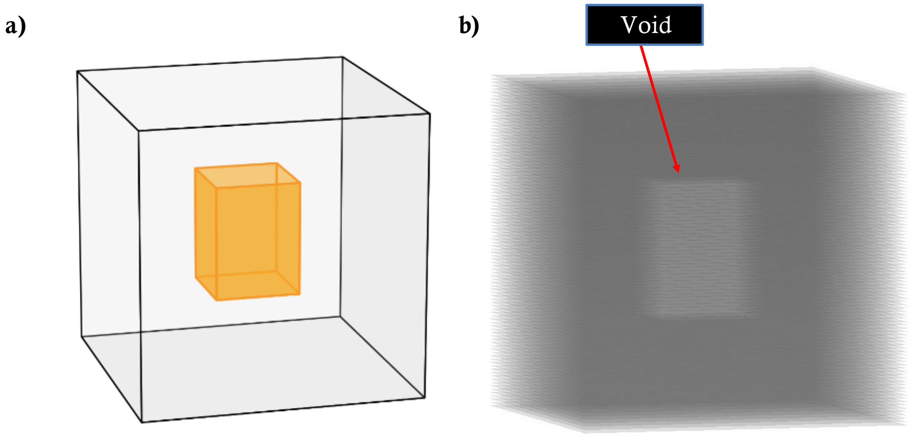

Figure 3. Defect detection when 2D layers are concatenated to create a B-Scan of printed component.~~.~~

The ultrasonic monitoring system employed in this research comprised an Epoch 600 ultrasonic flaw detector manufactured by Olympus, Breinigsville, PA, USA operating with a 5 MHz transducer. The transducer was strategically positioned adjacent to a customized resin vat integrated into a commercially available Anycubic DLP printer. Modifications to the printer included customized adaptations of the resin vat and build platform to enable unobstructed ultrasonic signal propagation and precise in-situ layer monitoring. A commercially available resin, namely High Clear Resin, manufactured by Anycubic, was selected for this study to investigate its curing behavior under different exposure times and various spacings.

CONCLUSION

This study successfully developed and implemented an ultrasonic-based real-time monitoring system specifically tailored for Digital Light Processing (DLP) additive manufacturing. A 5 MHz ultrasonic transducer placed adjacent to the resin vat allowed continuous in-situ monitoring of each printed layer, enabling precise dimensional accuracy of approximately 0.2 mm. The system effectively detected internal flaws down to a size of 0.249 mm², demonstrating reliable defect identification during the print process. By linking ultrasonic signal characteristics directly to material behavior, we established a robust basis for creating accurate digital twins, facilitating adaptive control strategies to correct defects proactively during manufacturing rather than after completion. This real-time insight enhances production efficiency, reduces material waste, and minimizes post-processing requirements, crucial advantages for precision-intensive fields such as biomedical engineering and microfluidics.

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