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Development of LCD Projection-type Three-dimensional Continuous Printing System

Shih Hao Huang*, Cho-Pei Jiang** and Maziar Ramezani***

Keywords: Additive Manufacturing, Vat Photopolymerization, Dynamic Masking, Continuous Production.

ABSTRACT

Vat photopolymerization (VP) technology is one of additive manufacturing (AM), commonly known as 3D printing, utilizes the light with proper wavelength to expose the photocurable resin inducing solidification by photopolymerization reaction. The existing AM machines face limitations in achieving mass production as they are designed for single-product output. This study proposes an innovative VP-based approach incorporating a liquid crystal display (LCD) to generate digital dental model slices. These slices undergo solidification using specific wavelengths, resulting in the creation of resin dental models through layered solidification. This study presents a groundbreaking continuous printing method that seamlessly integrates VP technology, post-processing, and storage. The primary objective is to facilitate the mass production of dental molds. The system comprises a storage unit capable of accommodating 24 models, a 13.3-inch LCD for simultaneous printing of six models, a magnetic stirring cleaning area, a 405 nm backlight unit, and an integrated human-machine interface developed in-house. This setup demonstrates the capability to produce 144 customized dental models suitable for sequential braces. Experimental results validates that the developed system is a comprehensive solution for the mass production of customized dental models. This advancement not only significantly reduces the involvement of staff but also streamlines the overall production time. The incorporation of a standardized and stabilized human-machine interface further enhances the customization process, marking a significant step forward in the field of dental model manufacturing.

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**Graduate Student, Graduate Institute of Manufacturing Technology, National Taipei University of Technology, Taipei, Taiwan 10608*
***Professor, Dept. of Mechanical Engineering, National Taipei University of Technology, Taipei, Taiwan 10608*
****Professor, Department of Mechanical Engineering, Auckland University of Technology, 55 Wellesley Street, East Auckland City, New Zealand*

INTRODUCTION

Additive Manufacturing (AM), according to ASTM International standards, encompasses seven distinct technologies. Among these, VAT Photopolymerization (VP) relies on light energy, utilizing liquid polymer resins as the primary material. The process involves using a specific wavelength of light to trigger a cross-linking reaction in the photopolymer resin, resulting in its solidification. Layer-by-layer stacking follows, forming intricate three-dimensional objects. This technology boasts advantages such as high-resolution surface finishes and cost-effectiveness, making it an ideal solution for digital dentistry applications (Lalatovic Andjela et al., 2022; Mohd Javaid et al. 2019; Jiang et al. 2022). Currently, the production of dental customized products remains on an individual basis, with the prospect of achieving automated continuous production still distant. The primary challenge lies in meeting the demands of continuous production due to the unique nature of customized products. However, in digital dentistry, sequential orthodontic models offer a promising avenue to fulfill the requirements for mass-customized continuous production.

In orthodontic treatment, the treatment process typically involves creating a series of 12 to 36 sets of models. The production of clear aligners follows a multi-step procedure, beginning with the extraction of digital dental models through 3D scanning. Subsequently, these models are arranged using layout software, sliced with specialized slicing software, and then 3D printed. The printed dental models undergo thermoforming with an orthodontic thermoformer, and the final step involves precision cutting using CNC or laser techniques to produce a comprehensive set of clear aligners, as depicted in Figure 1 (Impellizzeri, A. et al. 2020; Tsolakis, I.A. et al. 2022; Sonam Sehrawat et al. 2022). Given the intricate nature of this process and the need for multiple sets of models, there is an urgent demand for the development of technology that enables continuous, mass-customized printing of digital dental models.

TECHNICAL REVIEW

This study proposes the following four key points as solutions for continuous production in additive manufacturing for the dental industry:

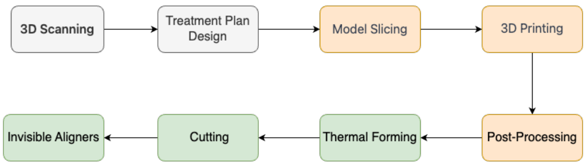


Fig. 1. Continuous mass customized digital dental model printing production technology

Additive Manufacturing Continuous Production

The mass production of products through additive manufacturing technologies has witnessed a substantial rise. Cumbersome manual tasks, such as pre-print mounting on the forming platform, have been replaced by robotic arms to augment productivity. This shift also enables the creation of an automated additive manufacturing production line capable of producing a diverse range of products in series.

Cloud-based Monitoring and Operation

Continuous production equipment for additive manufacturing may need to function either in series or in parallel, potentially involving multiple devices or a single device connecting to numerous users to boost efficiency. In such situations, the integration of cloud technology becomes imperative to enhance usage rates or provide early warnings regarding machine conditions.

Automated Post-processing

While additive manufacturing operates as a layer-by-layer fabrication method, there are several post-processing necessary. For instance, models produced through photopolymerization require post-curing, and the removal of supports is essential.

Automated Storage Systems

Each printed object has its identification method. After printing and post-processing, the focus shifts to how to deliver each customized item to the customer for use or further processing, such as CNC machining or reverse scanning for comparison. This necessitates the development of a storage system for holding purposes.

This research aims to create a solution for continuous production in digital dental technology through additive manufacturing. It combines automatic placement of the forming platform by robotic arms for printing and leverages optimized post-processing. By using automated storage, the printed items are stored in modular units of the system. The goal is to achieve 24-hour continuous production and produce a certain number of dental models, considering factors such as equipment cost, print size, and volume. The core printing process for this research is based on large-area LCD bottom projection digital light processing technology using a 13.3-inch LCD. The objective is to develop an automated system for continuous production of digital dental models through additive manufacturing.

AUTOMATED LARGE-AREA LCD PROJECTION SYSTEM FOR CONTINUOUS DENTAL MODEL PRODUCTION

The developed system is designed around a 13.3-inch monochrome LCD panel and an in-house developed backlight module. It specializes in handling photopolymer resins tailored for digital dental models. The system is structured with axial movement, seamlessly linking the forming plate storage area, pre-print zone, 3D printing region, post-curing space, and storage area, as illustrated in Figure 2. To optimize for mass production demands, our approach involves the incorporation of two independent three-dimensional printing systems, each handling specific printing tasks. Curing is accomplished through light projection gates, accompanied by Z-axis layer thickness control, aiming to deliver digital dental models that adhere to industry standards and seamlessly integrate into the production line.

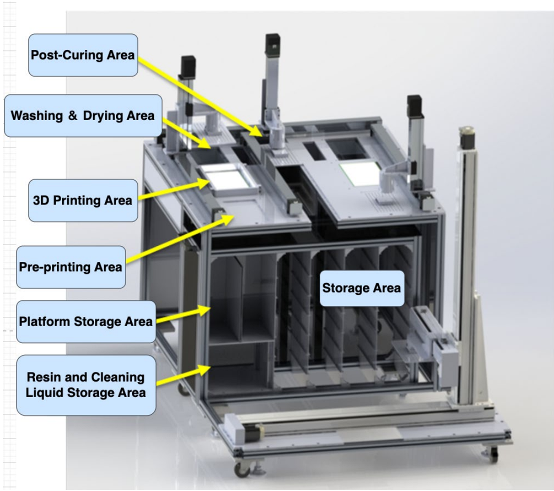


Fig. 2. Introduction to the areas of the machine.

The machine structure in this study is based on a framework constructed from 4040 aluminum extrusions, featuring an internal structure crafted from fabricated sheet metal components. The exterior is encased in a combination of sheet metal and acrylic panels. The machine's overall dimensions are 1870mm×1370mm×1840mm, with the forming area measuring 300mm×166mm×200mm. Figure 3 illustrates the comprehensive framework, encompassing the printing system, post-processing system, storage system, air purification system, axial motion control system, and the control system.

The machine control system is orchestrated by a computer acting as the supervisory controller, seamlessly integrated with the WMX3 software for axis motion and I/O control. This setup harnesses the distributed, ultra-high-performance capabilities of multi-core CPUs, optimizing computational speed. Furthermore, EtherCAT (Ethernet for Control Automation Technology) is employed for network control, eliminating the necessity for additional axis control cards and dedicated controllers. This technology is particularly well-suited for high-speed, multi-axis synchronous control across diverse manufacturing and automation applications. The primary emphasis is on managing storage and control button I/O, along with the precise positioning of the three-axis robotic arm servo motor in the storage system. This approach facilitates comprehensive planning of electronic control hardware.

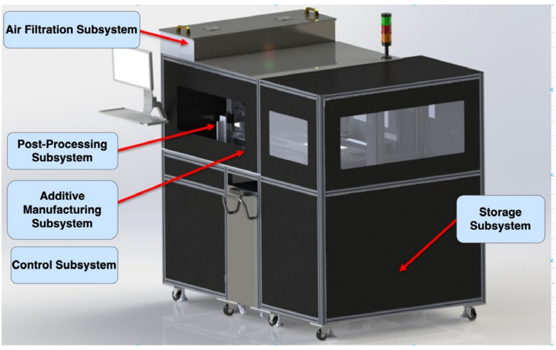


Fig. 3. Machine architecture overview.

For post-processing system control, this study adopts MediaTek's MT7697 microcontroller chip as the firmware core, illustrated in Figure 4. The MT7697 is a highly integrated system-on-chip featuring a Cortex-M4 microcontroller, a Wi-Fi subsystem, and a low-power Bluetooth subsystem. Its development platform is managed with the Arduino IDE for compatibility, offering superior performance and stability compared to the standard Arduino Mega2560. With built-in Wi-Fi and Bluetooth capabilities, it enables direct usage in future cloud management system development, eliminating the need for additional module expansion. The control system encompasses features such as dual-axis motion, proximity switches, a cleaning magnet stirrer module, and a post-curing process module.

The supervisory control system in this study is developed using the C# programming language within Microsoft Visual Studio 2018. Serial port and EtherCAT communication protocols serve as the primary means of communication. The core process involves workstation operators placing orders through the supervisory control system and executing tasks such as retrieval, printing, post-processing, and storage, facilitated by diverse communication protocols and I/O judgments.

The human-machine interface integrated into the supervisory control system incorporates features such as insurance confirmation, storage status monitoring, printer system monitoring, post-processing system monitoring, communication port connection status display, an activation panel for automatic control settings, and custom commands, as depicted in Figure 5.

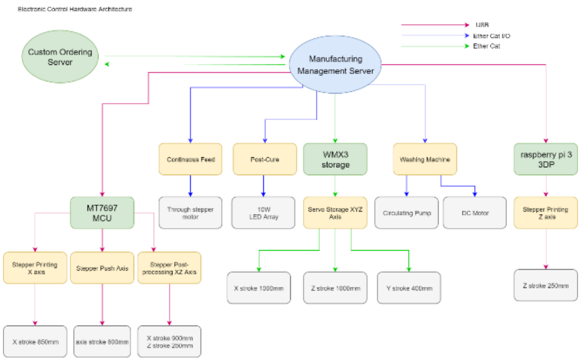


Fig. 4. Electrical control hardware architecture diagram.

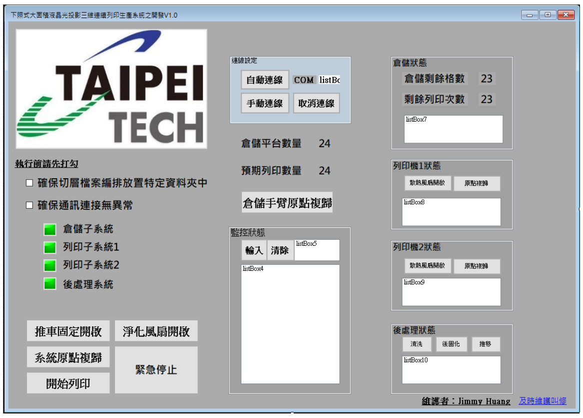


Fig. 5. Human-machine interface.

PRINTING AND POST-PROCESSING WAREHOUSE VERIFICATION

The machine developed in this study incorporates a single-axis robot to facilitate continuous production by transferring the forming platform. Positioned above the forming platform is a base composed of ferromagnetic metal, complemented by a robust 24V electromagnet for magnetically manipulating the extraction and placement of the forming platform. The primary variable load during the gripping process, apart from the forming platform's weight, is the downward force generated during the photopolymerization molding process as it prints.

In the curing phase, when the resin adheres to the bottom of the resin vat's PTFE film, a downward force emerges during the lifting movement of the Z-axis, resulting in the resin peeling off from the vat, termed the vacuum peeling force. However, as the Z-axis ascends to a predetermined height and descends to the next layer for curing, a resin backflow force ensues due to the resin's resistance when the platform moves upward in the resin. This phenomenon is referred to as the resin backflow force.

This experiment focused on measuring the maximum vacuum peeling force, maximum resin backflow force during the photopolymerization curing process, and the magnetic force of the strong electromagnet in its load verification analysis. To capture these forces during printing, an S-type load cell sensor, with a maximum range of 10 kilograms from High Precision Sensors Inc., was affixed to the printing axis. The electromagnet then lifted the forming platform.

The measurement procedure involved setting the bottom layer light exposure time to 20 seconds and curing the entire area. Subsequently, the forming platform was raised at a speed of 40mm/min. The recorded vacuum peeling force was approximately 31.7 Newtons, while the resin backflow force measured 26 Newtons, as illustrated in Figure 6.

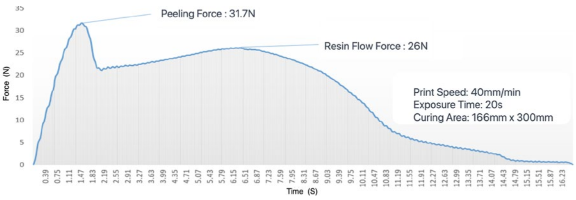


Fig. 6. Photopolymerization curing pulling force behavior.

The objective of this experiment is to verify whether the post-processing procedure can effectively remove the uncured resin from the models after each printing session and ensure clean storage of the models. The primary goal, besides thoroughly eliminating residual resin, is to control the overall time taken to complete cleaning and post-curing activities as quickly as possible.

After the printing process, the forming plate and the models harbor uncured resin. Directly subjecting them to post-curing would compromise the dental models' curvature features. In previous practices, ethanol, delivered through a high-pressure sprayer, was used for cleaning. However, this method often yielded uneven cleaning, proved time-consuming, and resulted in rapid ethanol evaporation. Consequently, this research has transitioned to a cleaning method utilizing a magnetic stirrer, supported by a solvent circulation system. Resin sediment washed off during cleaning is transported back to a 15-liter plastic container within a storage cart through a peristaltic pump and silicone tubing. This setup facilitates sedimentation and replenishment of clean ethanol. The magnetic stirrer's operational time can be programmatically set to 5 minutes. Test results indicate that a speed of 1000 rpm/min and a short duration effectively clean both the models and the forming plate simultaneously. This method meets research requirements and offers more uniform cleaning compared to manual methods. Additionally, it allows for the quantification of each cleaning interval and reduces the risk of ethanol vapor inhalation in the air, as depicted in Figure 7.

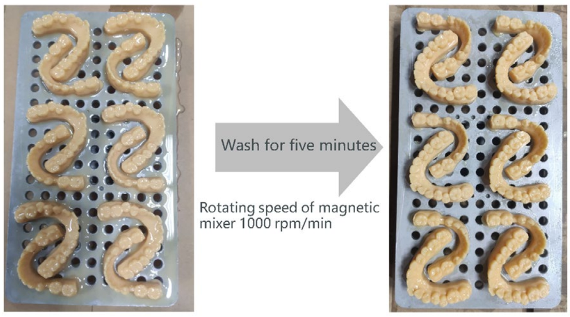
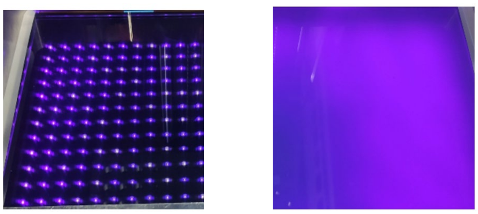


Fig. 7. Results before and after cleaning process.

Furthermore, the dynamic light masks are created utilizing an LCD screen that displays the layer pattern, drawing energy from a backlight panel positioned at the bottom. However, the design of the backlight panel, with LEDs not uniformly distributed across the entire surface, leads to pronounced dark areas during light mask projection. This uneven design results in varying curing strengths across the printing area, impacting the precision of the final digital dental models. To rectify this concern, optical diffusing films and prism brightening sheets can be utilized to achieve a uniform and parallel distribution of light.

A prism diffusing film was employed, boasting a haze of 65% to ensure uniform light distribution. Additionally, a 3M composite prism brightening sheet was used to capture light emitted from various angles of the backlight panel, redirecting and intensifying it to enhance forward brightness. The amalgamation of the composite prism sheet and the diffusing film serves not only to alleviate moiré patterns, uneven light sources, and other artifacts but also to deliver a clear, bright, and consistent display effect, as depicted in Figure 8 (a). The sequential arrangement of this combination is illustrated in Figure 8(b).



(a) (b)

Fig. 8. Projection screen (a)before light uniformity(b) after Light Uniformity.

This study utilized the spectrophotometric flicker illuminance meter for measurements (SFIM-400, Yuanfang Optoelectronics, Taiwan). The nine-point light uniformity measurement method was employed to assess the differences in luminance uniformity before and after achieving light uniformity. This approach entails delineating nine equal length and equidistant areas above the LCD panel and directly measuring them using the spectrophotometric flicker illuminance meter. Before achieving light uniformity, the uniformity was only 31%, as illustrated in Table 1. However, after realizing light uniformity, the uniformity significantly increased to 80.74%, as indicated in Table 2. This notable improvement in light uniformity before and after clearly underscores the enhancement in the precision of the printed digital dental model products.

Table 1. Results of pre-measurement of light uniformity.

Before Installing the Optical Filter

Irradiance (W/m²)	Irradiance (W/m²)	Irradiance (W/m²)
3.11	6.19	7.90
4.67	7.25	9.93
9.94	9.75	8.73

Luminance Uniformity (U) = Lmin/ Lmax X 100%= 3.11/9.94*100% = 31%

Table 2. Results of post-measurement of light uniformity.

After Installing the Optical Filter

Irradiance (W/m²)	Irradiance (W/m²)	Irradiance (W/m²)
4.36	5.40	4.38
4.66	4.64	4.52
4.58	5.27	4.42

Luminance Uniformity (U) = Lmin/ Lmax X 100% = 4.36/5.40*100% = 80.74%

The machine developed in this study has successfully quantified numerous processing parameters, allowing for the precise printing of digital dental models. To evaluate differences compared to conventional processing methods, this research specifically focuses on comparing human labor time and printing time. As part of this experiment, a 3D printing device with similar specifications, the Transform 13.3-inch LCD photopolymerization 3D printer manufactured by Phrozen Tech Co., Ltd. (as outlined in Table 3), will be employed. A comprehensive continuous production analysis will be conducted, comparing it with the continuous production equipment developed in this study. The distinctions between the two production processes are outlined in Table 4, providing an analysis of the production cycle for multiple sets of digital dental models.

After conducting multiple printings and timing measurements for orthodontic models on both the LCD Projection-type Three-dimensional Continuous Printing System and the Transform 13.3-inch LCD photopolymerization 3D printer, it was observed that the LCD Projection-type Three-dimensional Continuous Printing System excels in efficiency, particularly in the setup of the forming platform and post-processing. This proficiency diminishes the need for manual intervention. Consequently, this not only enhances the operators' utilization rate but also standardizes production times through the integration of automation technology. By reducing uncertainties linked to manual operations, the system enhances the stability and overall efficiency of production.

	Continuous printing system							other						
	Print settings	1st platform movement	Print	2nd platform movement	washing process	Post-curing	Storage	Print settings	1st platform movement	Print	2nd platform movement	washing process	Post-curing	Storage
Print once	5min 30sec	19sec	50min	2min	5min	5min	1min7sec	50sec	32sec	75min 40sec	55sec	6min	10min	
Print twice		22sec	50min 30sec	2min	5min	5min	1min5sec	60sec	31sec	75min 45sec	45sec	6min30sec	10min	
Print three times		24sec	50min 30sec	2min	5min	5min	1min	65sec	36sec	75min 30sec	50sec	6min45sec	10min	
Average time	1min 55sec	21.6sec	50min 20sec	2min	5min	5min	1min4sec	58.33sec	33sec	75min 38sec	36.6sec	6min25sec	10min	
Total time	224min3sec=3hr44min3sec							282min33sec = 4hr40min 33sec						
Average processing time	74min41sec							94min11sec						

Table 3. The transform process necessitates time.

	Continuous printing system							other						
	Print settings	1st platform movement	Print	2nd platform movement	washing process	Post-curing	Storage	Print settings	1st platform movement	Print	2nd platform movement	washing process	Post-curing	Storage
Print once								50sec	32sec		55sec	6min	10min	
Print twice								60sec	31sec		45sec	6min30sec	10min	
Print three times								65sec	36sec		50sec	6min45sec	10min	
Average time	1min 50sec							58.33sec	33sec		36.6sec	6min25sec	10min	
Total time	5min 30sec							56min 19sec						

Table 4. The machine developed in this study process necessitates time.

CONCLUSIONS

This study has devised a bottom-up, large-area LCD light projection three-dimensional continuous printing production system with the goal of consolidating batch printing for diverse digital dental models. The objective is to streamline various production processes, achieve synchronized continuous production, and substantially minimize manual intervention. Through the automation of the continuous production flow, the system not only simplifies the production process but also significantly diminishes production time. This transformation shifts the conventional layer manufacturing paradigm towards an automated continuous manufacturing approach. The innovation is anticipated to make a positive impact on future technological development by enhancing machine efficiency and production stability.

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