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Reviewed Paper

Towards the Fabrication of a 3D Part with Selective Laser Additive Manufacturing Acousto-Optic Light Engine (SLAM-ALE)

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Abstract

Stereolithography (SLA) additive manufacturing (AM) uses a laser system with galvanometric mirrors and lenses to selectively polymerize liquid photosensitive materials into 3D parts. Fine details require small beam sizes for high spatial resolution, however large parts with small features can require prohibitively long build times. A pair of acousto-optic deflectors (AODs) can be used to rapidly trace the beam perpendicular to the galvo scan, thereby eliminating the tradeoff between speed and resolution.

In a previous work, a simulation of a galvo and AOD SLA system was developed to examine the effects of individual processing parameters. In this work, a custom prototype system is used to validate the ability to dynamically adjust the track width, and a more advanced system is developed and used to demonstrate the ability to use combined AOD and galvo motion to scan fine features.

Introduction

Stereolithography is an additive manufacturing process wherein a laser is steered using beam forming optics and galvanometric mirrors onto a vat of photopolymer resin to selectively polymerize a cross-section of a part. By recoating with a new layer of resin and repeating the process, full 3D parts with complex geometries are produced.

The SLA process has a fundamental tradeoff between build speed and part resolution. Because the exposure of each slice is performed using individual scan vectors, slices with large areas will require many scans for full coverage, requiring long build times. Methods of improving build speed include increasing the scan speed, increasing the spot size, or using a different method of exposure such as digital light processing (DLP); but each method comes with limitations. The scan speed of the beam is limited by the mass and stiffness of the galvanometric mirrors. Increasing the laser spot size allows each individual scan to cover a larger area, increasing build speed but decreasing the potential resolution for small features. DLP exposes the full build plane at once using a UV lamp and digital micromirror device, but has inflexible resolutions, generates heat in the photopolymer vat, and cure depth is limited by UV source power.

Selective laser additive manufacturing with acousto-optic light engine (SLAM-ALE) is a novel system using two cross-axis acousto-optic deflectors (AODs) in series with a set of galvanometric mirrors (galvos) to increase the build speed of the SLA process by using AODs to dynamically vary the scanned track width, increasing build speed without increasing galvo scan speed or laser spot size. An AOD is an optical prism engineered to produce a desired beam diffraction, effected by using a piezoelectric transducer to introduce specific frequencies of acoustic waves therein. When a radio frequency (RF) signal is applied to the transducer, the signal is converted into an acoustic wave traveling as a compression wave through the prism. The longitudinal wave creates periodic compression and rarefaction and, via the photoelastic effect, locally affects refractive index to produce a Bragg grating. The exit angle of the first order beam is determined by the period of the Bragg grating, which is determined by the frequency of the RF signal. The access time of the device is determined primarily by the speed of sound in the medium and the optical beam diameter. The AODs used deflect the first order beam milliradians and can do so within 200 nanoseconds.

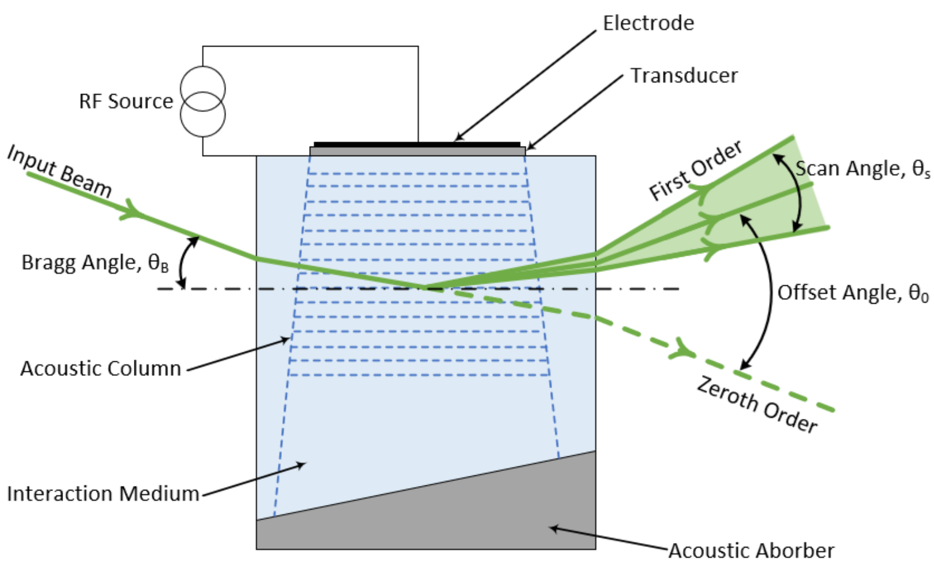

Figure 1: Acousto-optic deflector

To combine the advantages of the galvo's large angular range and the AODs rapid sweep speed, a vector is scanned using the galvos while the AODs rapidly sweep the laser spot perpendicular to the galvo path, dynamically altering the track width [1]. In a previous work, the use of AODs in SLA is introduced and a simulation of the process is developed based on the theoretical principles behind SLA and used to investigate how the processing parameters affect the final product [2]. SLAM-ALE was shown to potentially increase the speed of SLA by 60% compared to similar systems, and the results of simulation demonstrated the ability to use the AOD to vary the track width while tuning other parameters to optimize for part quality, allowing for increased build speed without sacrificing resolution [3]. In this work, a prototype SLAM-ALE system was built and used to prove the ability to use AOD and galvo movement to vary the track width. Based on experiments and lessons learned from the prototype, a more robust demonstrator system was designed, built, and used to produce parts demonstrating the capabilities of the SLAM-ALE system.

355 nm Prototype

A picture of the experimental prototype system with both AODs, galvos, f-theta lens, and build plate labeled is shown in Figure 2. The laser used in this system is a 355 nm continuous wave laser with peak power output of 100 mW, chosen because it was high quality and available. The AODs used are the L3Harris Acousto-Optic UV Deflector, H903, selected because they were an existing design that met the needs of this project [4].

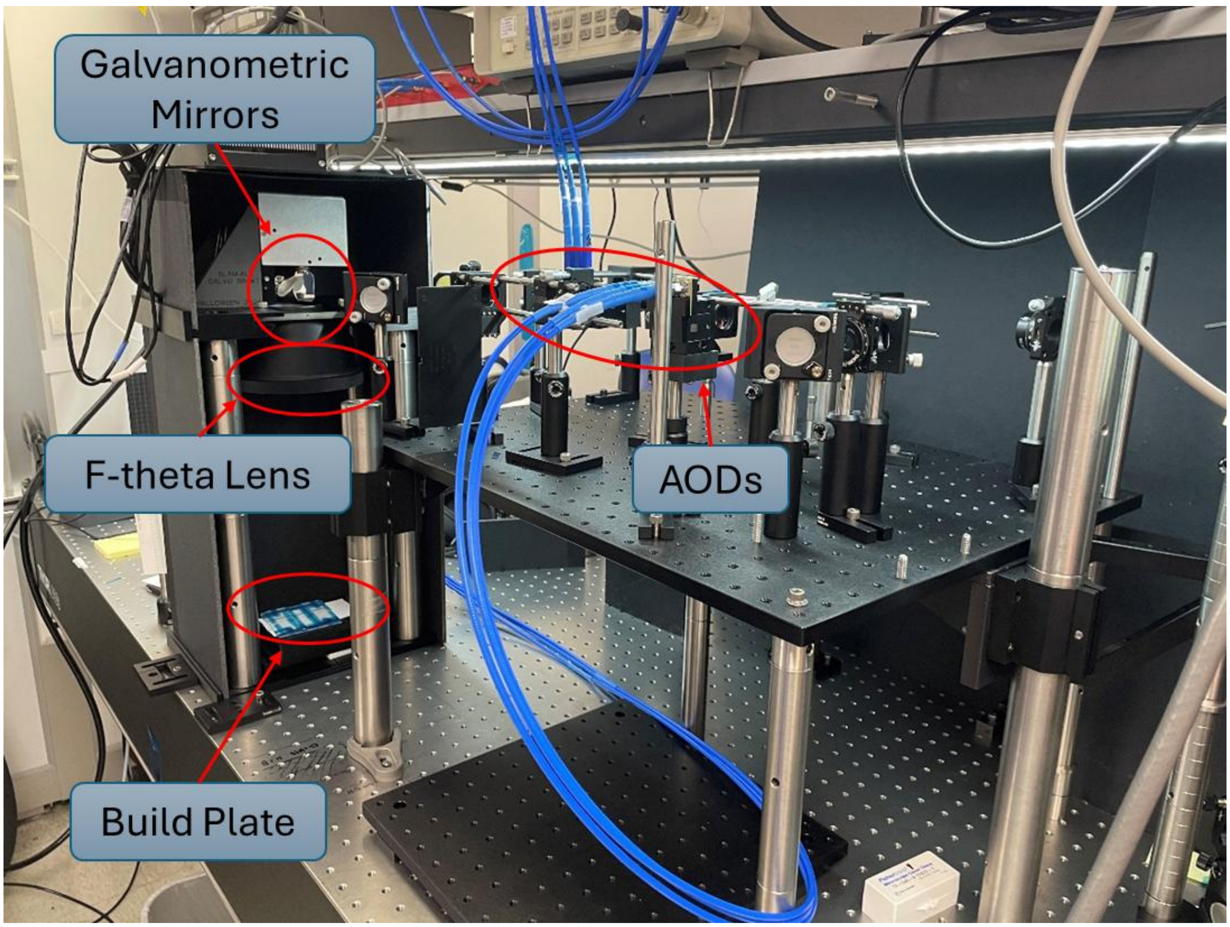

Figure 2: 355 nm prototype system

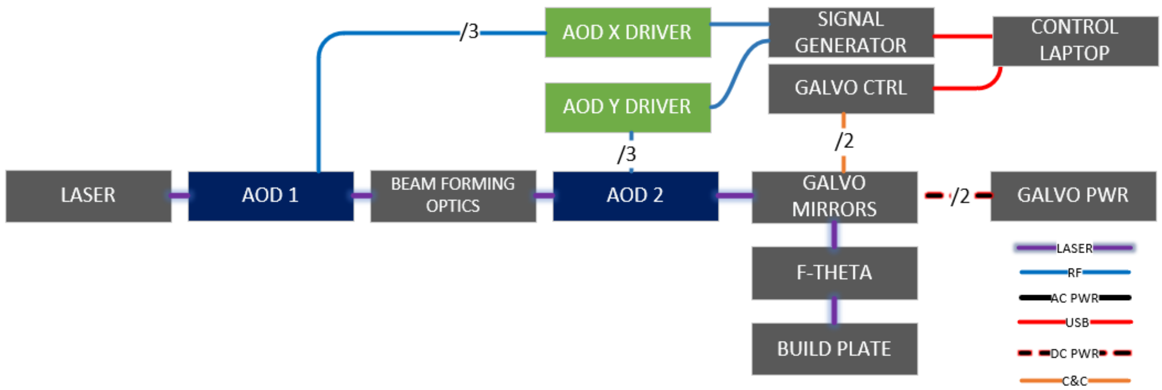

Figure 3: Block diagram of 355 system

Figure 3 shows a block diagram of the major components and the energy flow through the system. The beam passes through both AODs—configured to deflect the beam orthogonal to each other along the X- and Y- optical axes—to the galvo mirrors, through the f-theta lens, and to the build plate. The signal generator, a Liquid Instruments Moku Pro, sends two RF signals to two Spectronix RF drivers, which amplify, split, and phase-offset the signal before sending it to the two AODs. The signal generator and galvo controller are both connected to a computer controlling the system.

The laser spot size, build plane, and AOD diffracted spot displacement were measured by replacing the build platform with a scanning slit beam profiler. After finding the build plane location, the build platform was replaced and lowered by 1 mm to account for slide thickness. The $1/e^2$ laser spot diameter was found to be ~50 µm. Each AOD was aligned to a center RF frequency of 190 MHz, and sweeping the frequency by 20 MHz deflected the spot by ±80 µm.

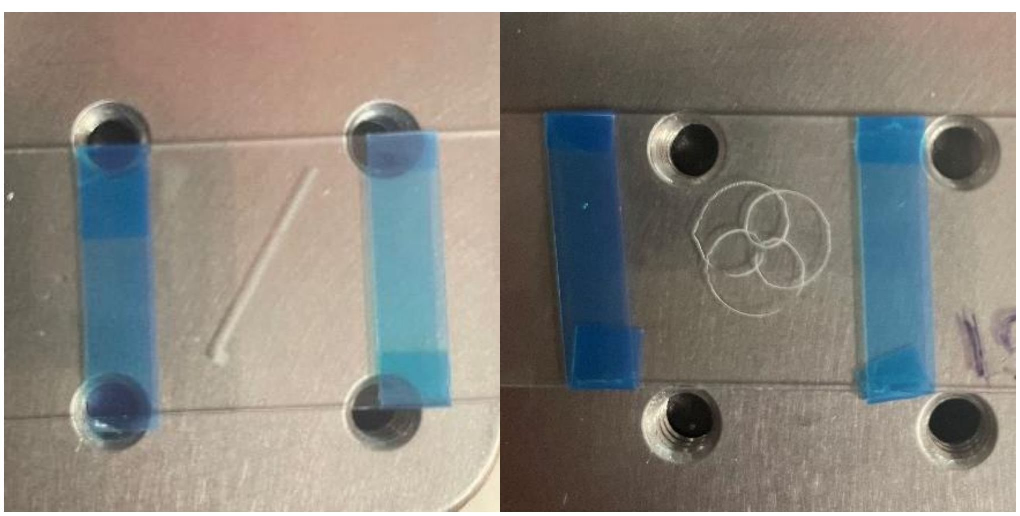

Figure 4: Two examples of samples produced by the 355 nm prototype system

Microscope slides were used as a substrate for samples scanned in the 355 nm prototype system. A razor blade was used to spread a layer of resin between two pieces of tape spaced one inch apart before the slide was placed on the build plate for scanning. In initial experiments, light reflected from the back of the glass slides caused an undesirable loss in resolution. The next round of experiments was performed using black aluminum foil taped to the slides, which was found to be suboptimal due to the resin failing to stick to the foil, and the foil's tendency to fold up at the edges. Ultimately, it was found that white clean room paper taped to the slides was the best solution for this early stage of experiments.

The galvo controller was programmed to send a series of voltages, each moving the galvo mirrors to a corresponding position, with a specified dwell time used to control the speed of the galvo scans. AOD sweeps were controlled separately from the galvos and set to either remain at a constant RF frequency, or to sweep a set frequency range, thereby sweeping the laser spot across the range of the respective AOD.

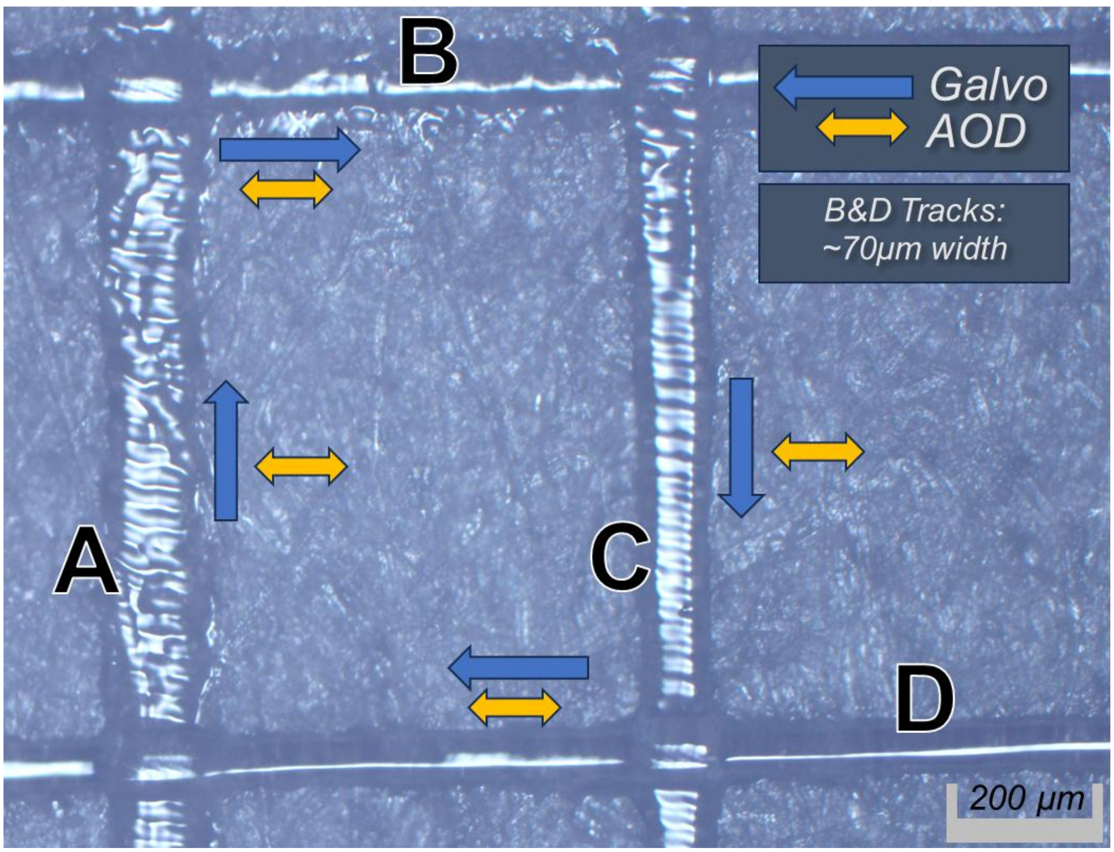

Figure 5: Experimental results from 355 nm prototype. Processing parameters in Table 1. Note that track width of A is wider than track width of B, and track width of C is wider than track width of D.

Through repeated evidence-based experimentation, a reasonable set of processing parameters was found to demonstrate the feasibility of the system and validate the modelling effort. Figure 5 shows the results from one such experiment; orthogonal galvo scan lines with equivalent fluence, scanning either parallel or perpendicular to the AOD sweep direction. The complete processing parameters used to scan the lines are provided in Table 1. Galvo-scanned traces A and B delivered more energy than scans C and D, achieved by reducing the scanning speed of the galvos while keeping AOD operation parameters constant (AOD 1 at constant center frequency and AOD 2 modulating ±20 MHz at 40 kHz). The differences in track width of scans A vs B and of scans C vs D prove the ability to manipulate the width of the cured track by controlling the relative motions of the AODs and galvos.

Table 1: Processing parameters for sample 60

	Lines A & B	**Lines C & D**
Laser Source Power	75 mW	
AOD 1	No modulation	
AOD 2	±20 MHz modulation at 40 kHz	
Galvo Dwell Time	1600 µs	1200 µs
Approximate Galvo Scan Speed	1.73 mm/s	2.31 mm/s

405 nm Demonstrator – Hardware

The experiments and results from the prototype informed the development of a more advanced system to serve as an experimental platform in the future. Figure 6 shows the demonstrator with its completed optical assembly. The optical train, though redesigned for 405 nm, is nearly identical to that of the prototype with the sole addition of a spatial filter to address the lower quality laser source beam shape. The laser source is a 365 mW, 405 nm continuous wave laser, and the AODs are the same H903 model used in the prototype. Mechanically, the system was designed to maximize robustness, featuring machined aluminum framing and a v-groove optical mounting system [5].

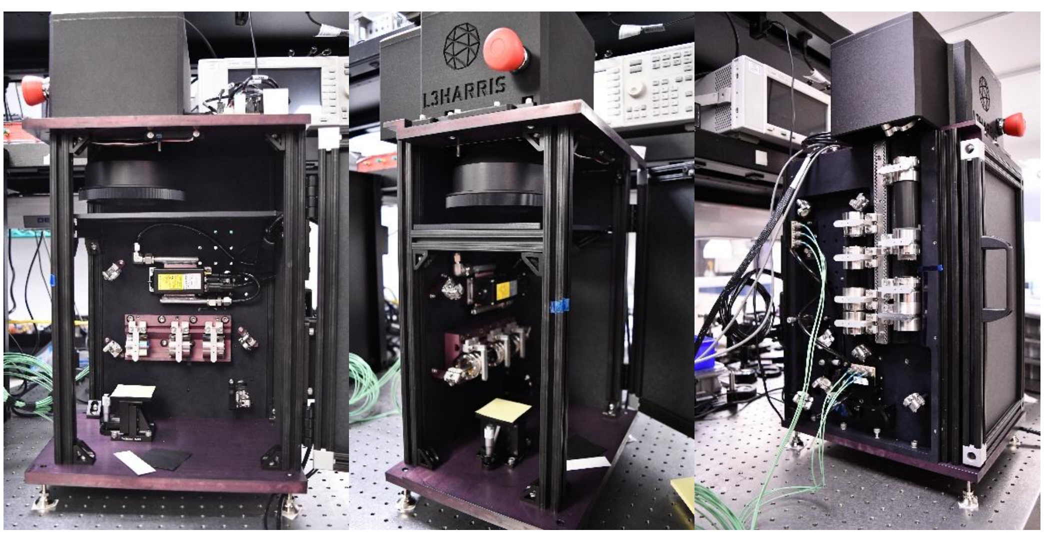

Figure 6: Left: front of demonstrator; Center: side of demonstrator; Right: back of demonstrator

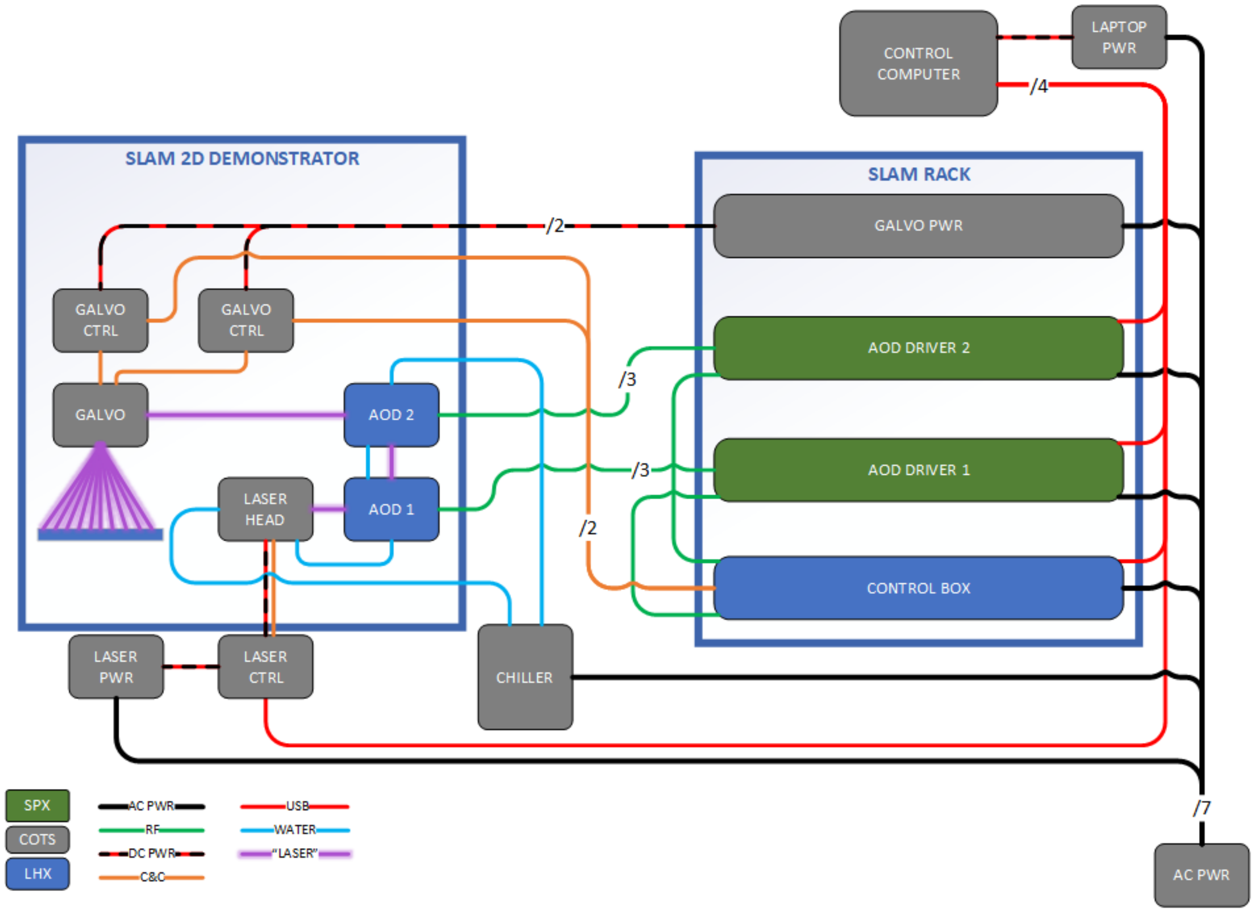

Figure 7: Diagram of major components of demonstrator

The control system architecture of the 405 nm demonstrator shown in Figure 7 is revised from the 355 nm prototype. The computer controlling the system is connected to the custom control box, which sends analog signals to the galvo controllers and generates two amplitude-controlled RF signals, sending those to the AOD drivers where they are amplified and split into three phase-offset channels, which are routed to their respective AODs.

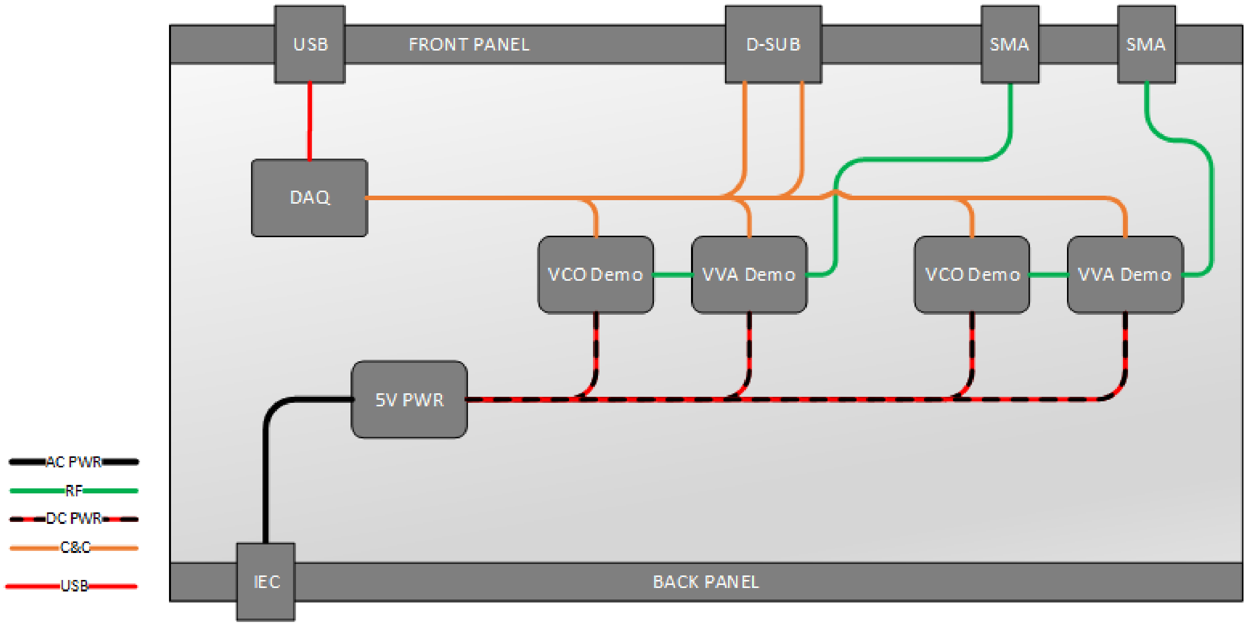

Figure 8: Control box architecture

The control box combines the functions of the Moku Pro and the standalone galvo controller into a single module, shown in Figure 8. A National Instruments (NI) data acquisition card (DAQ) controls the system using six analog output channels sharing a 1 MHz update rate. Within the box, these channels are routed as follows:

- Two channels: routed directly out of the box through the D-Sub connector to control the galvos
- Four channels: routed within the box to generate two RF signals. For each signal:
  - The first channel feeds a voltage-controlled oscillator (VCO), which maps the DAQ's voltage output to an RF frequency output
  - The second channel sets the gain of a voltage-variable amplifier (VVA), used to stabilize the RF power output of the VCO across the 180-220 MHz band

Both VCOs and VVAs are powered by a 5 V internal power supply. The inputs of the control box are data via USB and AC power. The outputs are two analog channels for X- and Y- galvo mirrors and two RF outputs for X- and Y- AODs.

405 nm Demonstrator - Software

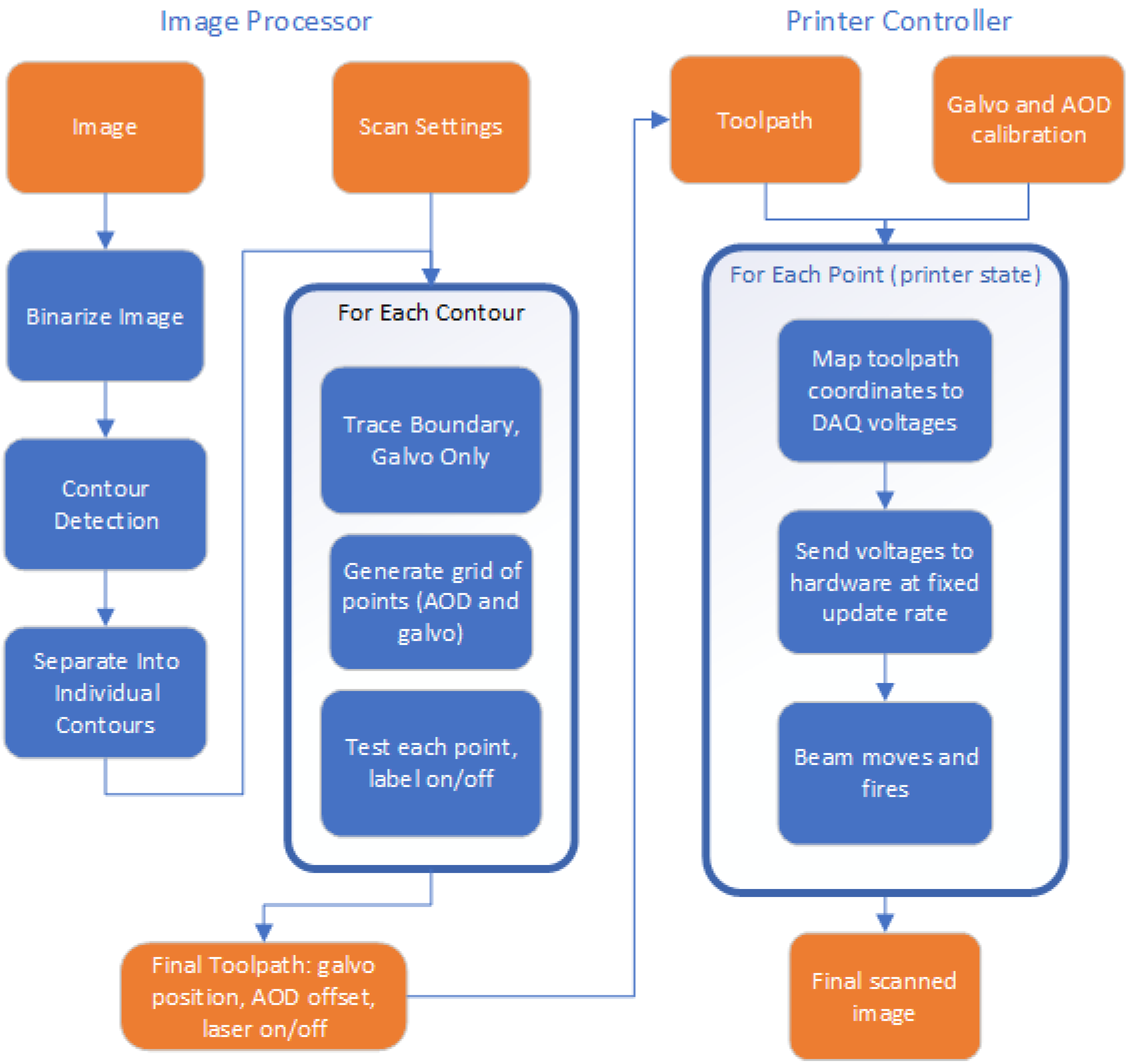

Figure 9: Block diagram of image processing (left) and printer control (right)

Figure 9 shows a flowchart of the control software used on the 405 nm demonstrator, which is separated into two parts: an image processor and a printer controller. The image processor accepts an image and printing parameters and generates a toolpath readable by the printer controller, which translates the toolpath into DAQ voltages. Figure 10 shows an example of an image going through the image processor. The image is binarized and separated into individual contours processed for two toolpaths: an outline shown in blue and an infill shown in red. When tracing the outlines, the AODs are set to constant frequencies while the galvos are used to scan the outline. The infill path is generated by covering the image with augmented galvo-scans (AOD sweep widened regions) and filling those with a grid of points located using coarse (galvo) XY coordinates and fine (AOD) XY coordinates and assigned an ON/OFF state respecting inclusion within the image's infill.

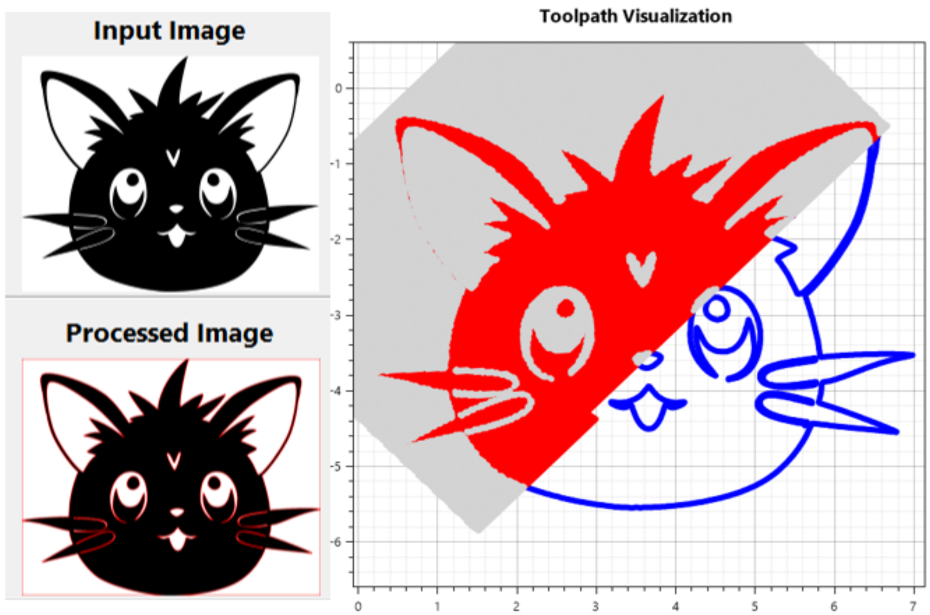

Figure 10: Upper left: original image; lower left: processed image indicating infill (black) and contour (red); right: generated toolpath visualization with edge-contour (blue) and partial AOD augmented infill galvo scans at build plane; toolpath visualization red indicates laser on, grey indicates AOD blanked laser.

The infill paths are combined into a single toolpath, consisting of a timeseries list of states: coarse galvo XY coordinates, fine AOD XY coordinates, and an ON/OFF state. The toolpath is read by the printer controller, which converts the coordinates into calibrated voltage values used by the NI DAQ to control the laser system. The designs of the calibrations are shown in Figure 11. Galvo positions are converted to voltages using a linear calibration. AOD offsets are mapped to VCO voltages using a second linear calibration. As a constant RF amplitude is desired across the RF frequency spectrum, a 2D linear fit based on both frequency and amplitude is used to control the VVA. In the case of an OFF state, VCO and VVA voltages are driven to zero to blank the beam.

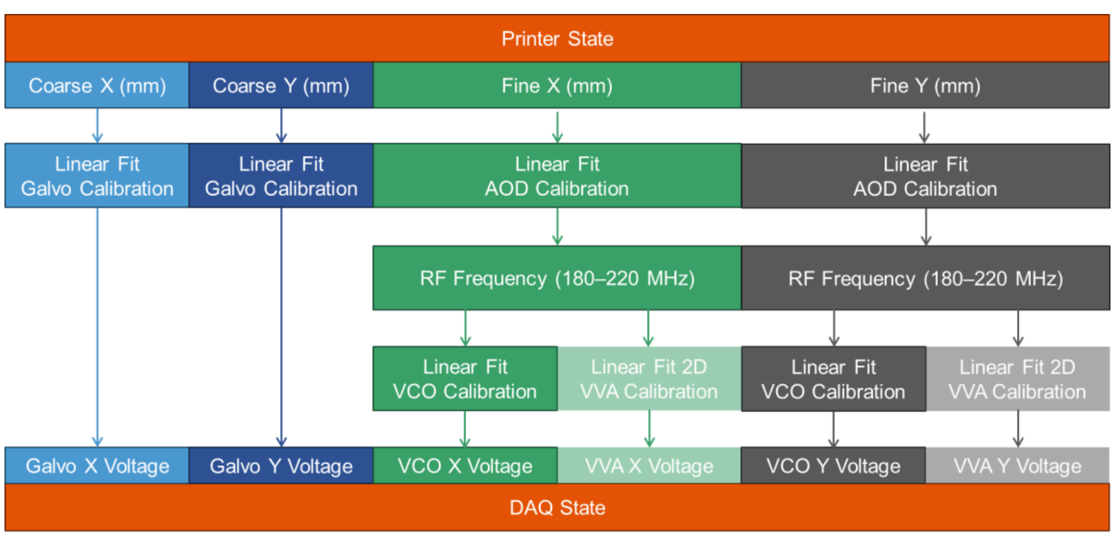

Figure 11: Printer controller calibration

405 nm Demonstrator Results

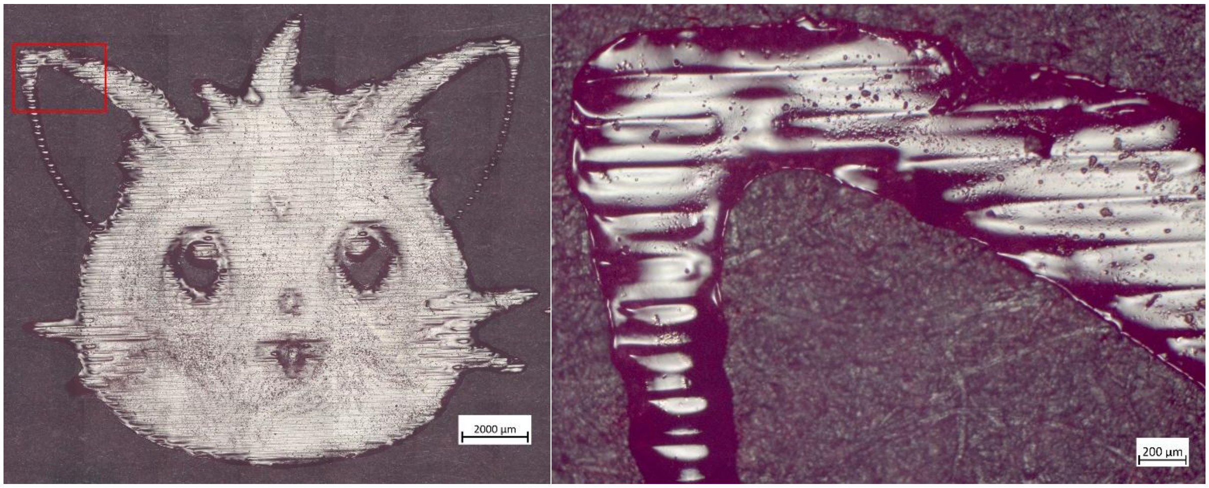

Figure 12: Left: 2D sample scanned on 405 nm demonstrator; Right: close-up of boxed region. Note that the inner edges of the ear were achieved without a contour scan.

Figure 12 shows a sample scanned on the 405 nm demonstrator using only the AOD-augmented infill toolpath. The edge-contour toolpath was not performed. The left shows the full printed image, and the right shows a zoom-in image of the left ear.

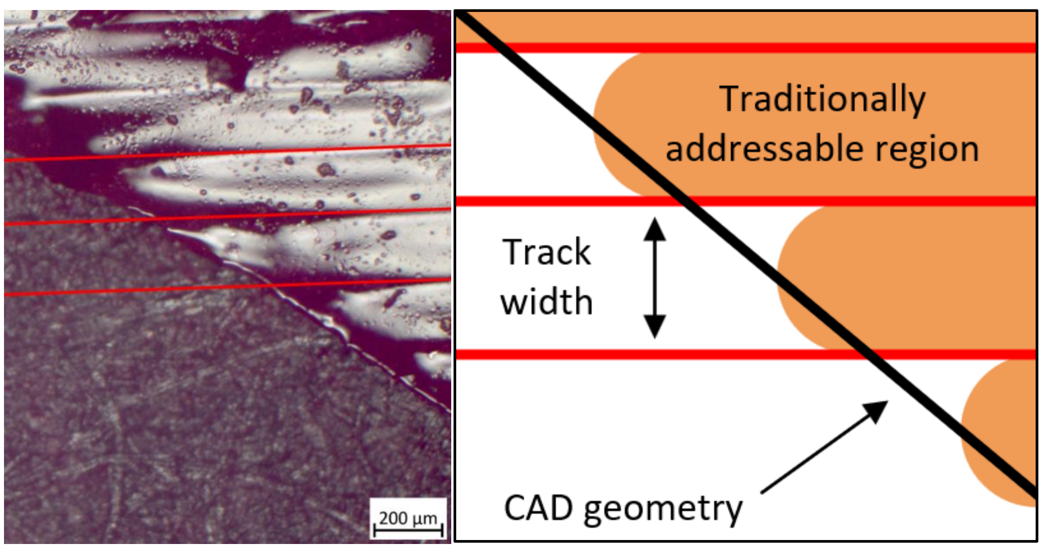

Figure 13: Left, alternate zoom of Figure 12, borders between adjacent tracks in red. Right: illustration of geometry traditionally scanned using equivalent size laser spot

On the left of Figure 13 is a closer zoom of the same sample, and on the right is an illustration of what this scan would look like if performed using a traditional SLA system. In both images, the red lines show the borders between tracks. Performing this scan with a traditional SLA system would have produced an effect similar to stairstepping often observed in the vertical direction of AM parts. Instead, the SLAM-ALE system uses the AODs' ability to locally modify the track width to produce a smooth diagonal edge.

Moving Forward

Now that SLAM-ALE has been demonstrated in a single layer, the next step is to incorporate a vat and recoating subsystem to enable the production of multi-layer (3D) structures. In the future, a replacement for the existing build plate will be designed and built, including a resin vat, build tray with vertical motion, recoater blade, and all associated controls.

The simulations as presented in the paper published in Solid Freeform Fabrication Symposium 2024 used an analytical solution to a moving beam [3]. However, the 405 nm demonstrator operates by jumping to discrete points at a specified clock speed. In future work, a discretized simulation will be developed that uses the same toolpath as the 405 nm demonstrator to validate the simulation approach and predict performance.

Conclusion

A prototype SLAM-ALE system was designed, built, and used to demonstrate the ability to locally modify the cured track-width in SLA through the coordinated use of galvos and AODs. Following success on the prototype, a more robust demonstrator system was developed and used to demonstrate the AODs' rapid beam positioning, producing a part with details finer than the nominal track width.

Works Cited

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