GLAZING VIRTUOSO

PAGE INTENTIONALLY LEFT BLANK

*ACKNOWLEDGEMENTS

IAAC FACULTY: *ALEXANDRE DUBOR, DANIIL KOSHELYUK, MARIELENA PAPANDREOU, ALDO SOLLAZZO, SOROUSH GARIVANI, VINCENT HUYGHE*

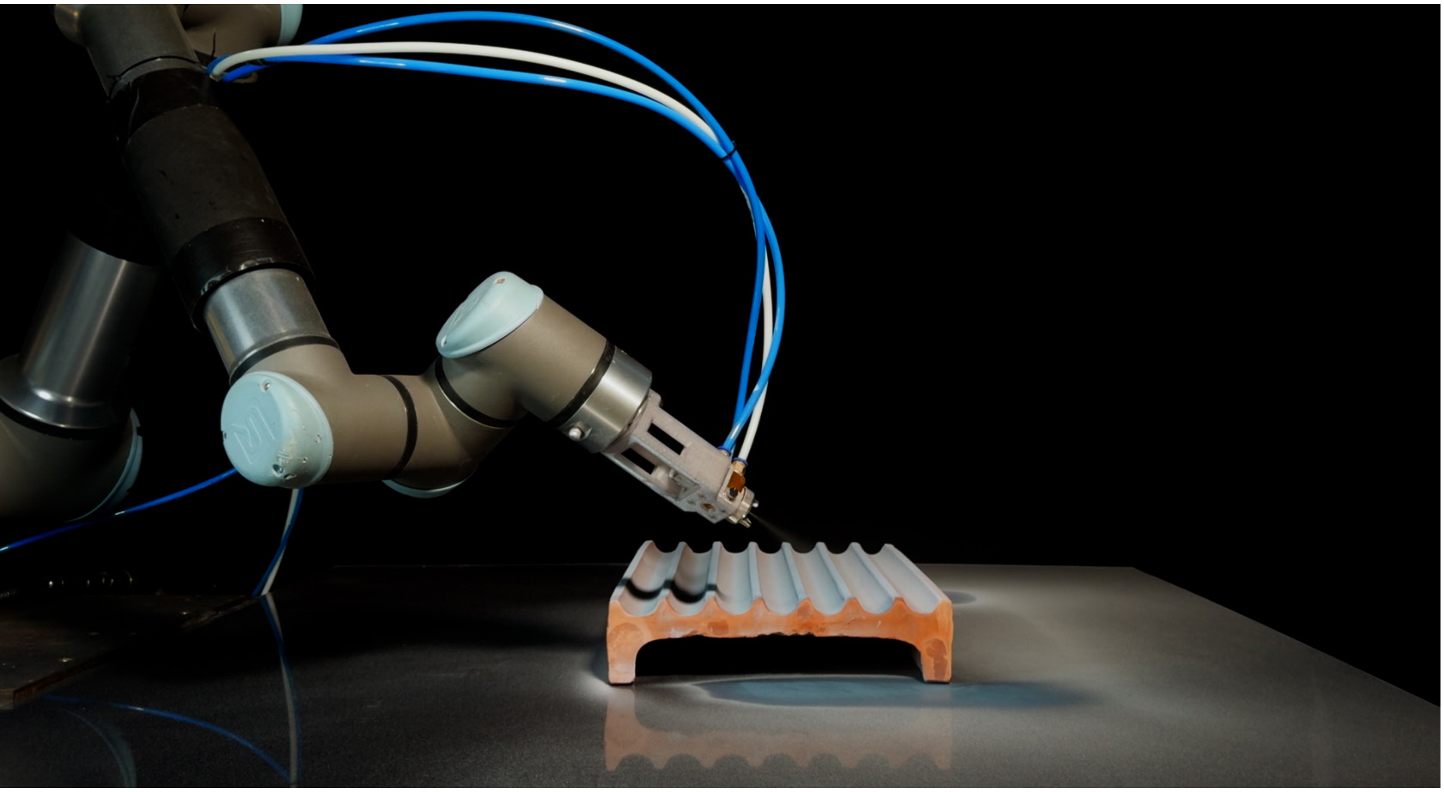
IAAC STAFF: *SHEIKH RIZVI RIAZ, SECIL AFSAR, PHILLIP WIENKAMPER*

IAAC COLLEAGUES: *MARIA LUIZA GOMES TORRES, FEARGAL MURPHY, FRANCISCO MARTINEZ*

KEMA CERAMICS: *PABLO OMAR PULIDO, DAIANA NUÑEZ SCHNEIDER*

Glazing Virtuoso

Ainhoa Arnaiz
IAAC
Andres Said Rodriguez
IAAC
Frank Henry Boy
IAAC
Oswaldo Veliz
IAAC



Project Brief

Glazing Virtuoso marks a pivotal shift in the spray glazing industry, where craftsmanship meets cutting-edge robotics to usher in a new era of creative expression and manufacturing precision. This project enhances creative workflows by seamlessly integrating intricate spray glazing techniques, that would blend in traditional artisanal craft empowering artists with unprecedented control that could foster a quite unique collaborative synergy between human expertise and robotic capabilities in the application of custom glazeing. From architectural masterpieces to bespoke installations, Glazing Virtuoso aims to set a new standard for the industry, blending tradition with innovation to redefine the possibilities of design and fabrication.

FIG 2 Studio RAP Ceramic House

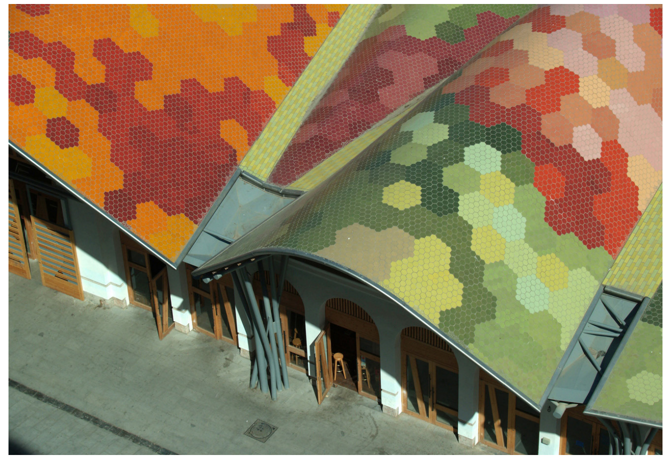


FIG 3 Ceramica Cumella - Santa Caterina Market

FIG 4 Adam Nathaniel Furman - Croydon Collonade

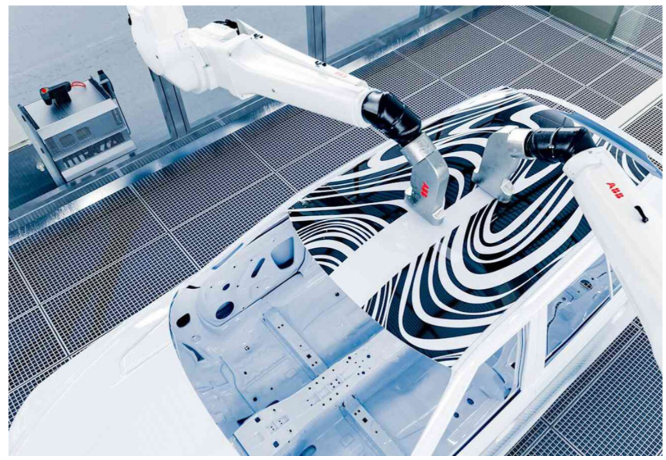


FIG 5 ABB PixelPaint

State of the Art

Glazing serves critical purposes in ceramic applications, including surface protection, light reflection, and heat insulation. Beyond functionality, it transforms ceramic objects into vibrant, colorful creations. This is equally vital in large-scale projects such as facades or roofs, exemplified by studios like Ceramica Cumella, Studio RAP, and Atelier ANF, which traditionally hand-glaze each piece. However, manual glazing is laborious and repetitive. To enhance efficiency, we propose integrating robots into the process. Robots ensure consistent application with minimal margin for error, significantly enhancing the precision of glazed finishes. (FIG. 2,3,4)

The automotive industry which has had large partnerships and an immediate impact in the adoption of technological innovation have been developing customizable automated options when it comes to finishing a car. Companies such as Mitsubishi and even Robotic giants like ABB have dwelled into the automotive spraying and introducing innovation such as with the Pixel Paint adoption. (FIG 5)

In household items such as toiletry the industry has become streamlined in automation where toilets, bathtubs, etc undergo a robotic glazing procedure to quickly produce thousands of pieces.

With this in mind we try to incorporate workflows seen across non-architecture industries and provide them as a possible architectural procedure to further increase the possibilities of large scale ceramic ware in the AEC Industry.

FIG. 6. ENGOBE

FIG. 7. ENGOBE

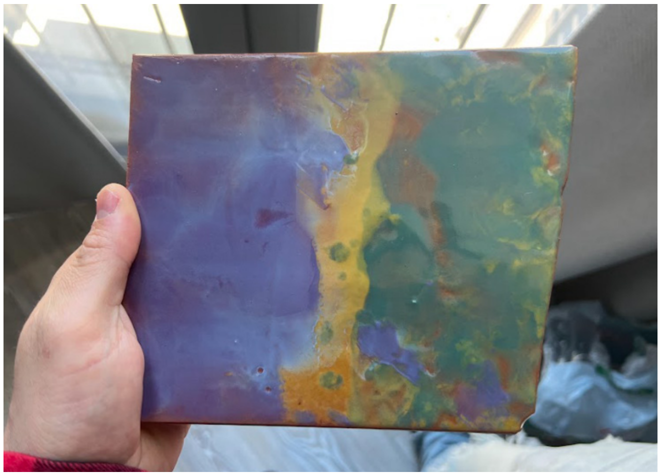


FIG. 8 GLAZING

FIG. 9 GLAZING ON 3D PRINT

Material

Ceramics are non-metallic, inorganic materials that are typically made from clay and other raw materials. These materials are formed into desired shapes and then subjected to high temperatures to achieve certain properties such as hardness, strength, and resistance to heat and chemicals. Ceramics are used in a wide range of applications, from pottery and sculpture to advanced engineering components.

In todays digital stage, processes such as 3D Printing with clay has become quite a rather common thing, yet its finishing process remains quite untouched. A perfect opportunity to discover new opportunities in finishing of ceramics on a more autonomous way exists.

Types of Glazes

Engobes
Glazes

Engobes

Engobes are a type of slip, which is a liquid mixture of clay and water, that is applied to ceramics before the final glaze. Engobes can be colored and provide a layer that can mask the natural color of the clay body, create a smooth surface, or provide a different texture. They are often used to prepare the surface for further decoration or glazing. Engobes can also be applied to wet stage clay, and go on the initial firing, unlike glazes(FIG 6, 7)

Glazings

Glazes are a type of coating applied to ceramics that can provide color, decoration, and functional properties like waterproofing and durability. Unlike engobe and its material properties, glazes undergo a chemical transformation where its silica turns to glass, thus giving its smooth and reflective finish. (FIG 8,9)

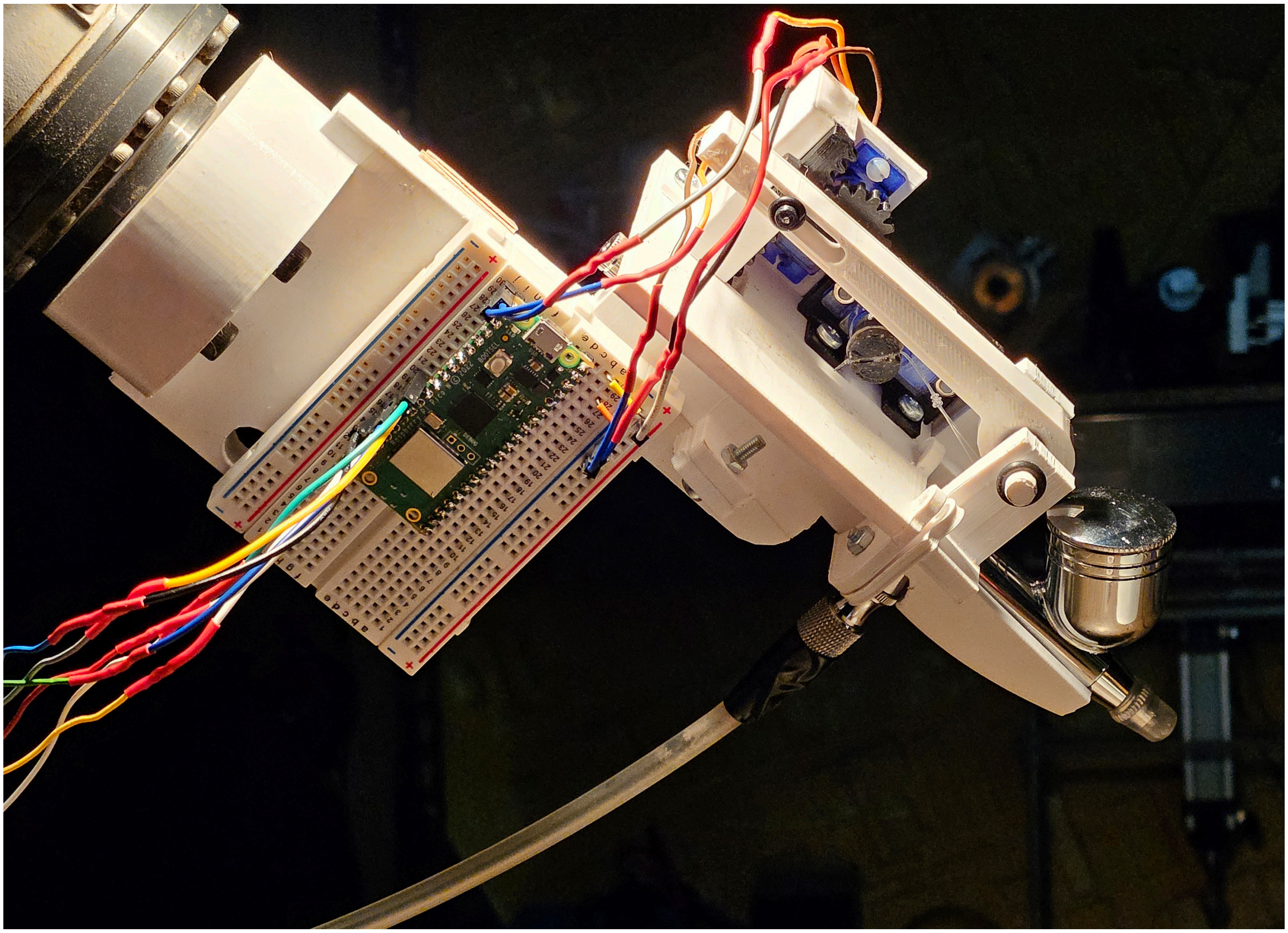


Fig 10 Air-Brush End-Effector

Robotic Adoption

Our first end-effector was meticulously designed to integrate a mechanism capable of executing the dual functions required by the airbrush: pushing down to regulate compressed air and pulling back to control paint flow. This design encompassed both mechanical and electronic elements, engineered to handle varying forces for each action. This precision allowed for intricate detailing in ceramic work. (FIG 10-14)

Information such as pull force and distance could change from plane to plane thus embedding information different aspects of the digital output onto different planes of the same toolpath. Questions

However, this setup proved impractical for large-scale projects like facades and roofs due to the extensive scale and quantity of pieces involved. Utilizing such a small-scale tool would be highly inefficient under these circumstances.

Therefore, we made the decision to transition to an industrial-grade tool. We developed a custom adapter for integration with the robot and began experimenting with various parameters such as pressures, speeds, distances, and increments to optimize control. This meticulous approach enabled us to achieve precise tool manipulation, despite inherent limitations. (FIG 16-19)

Through the use of an industrial sprayer tests of larger scale could be tested, architectural scale.

What could be the possibilities of integrating such a tool to a robot?

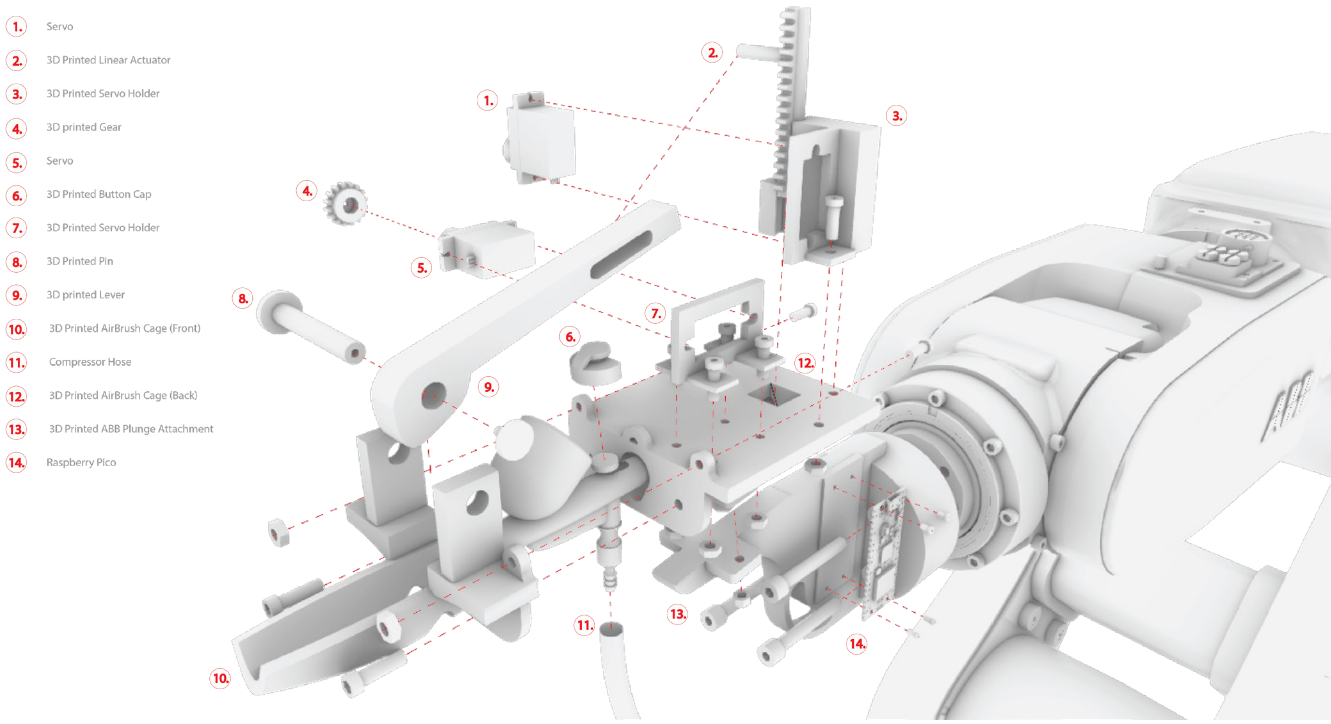


FIG . 11 EXPLODED KIT OF PARTS

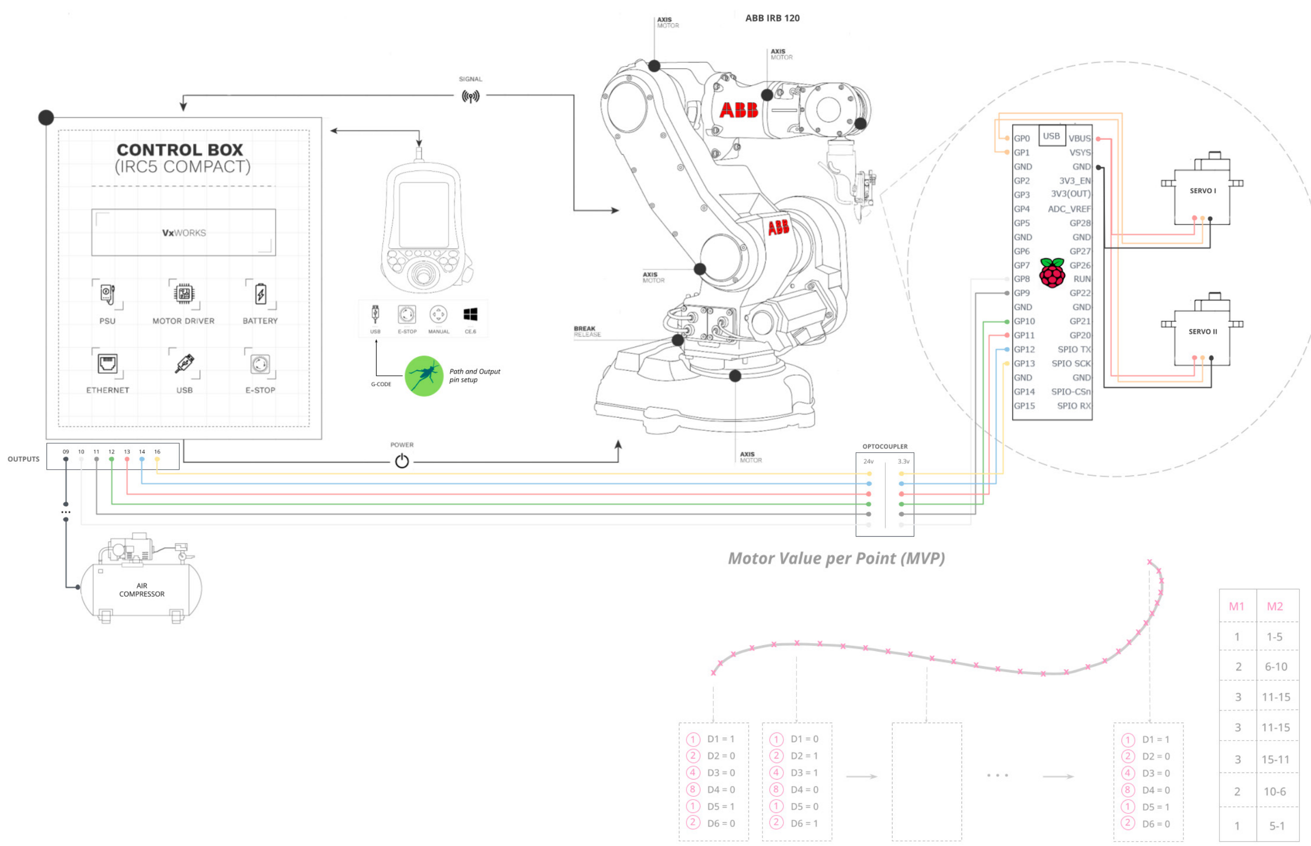


FIG 12. OUTPUT DIAGRAM

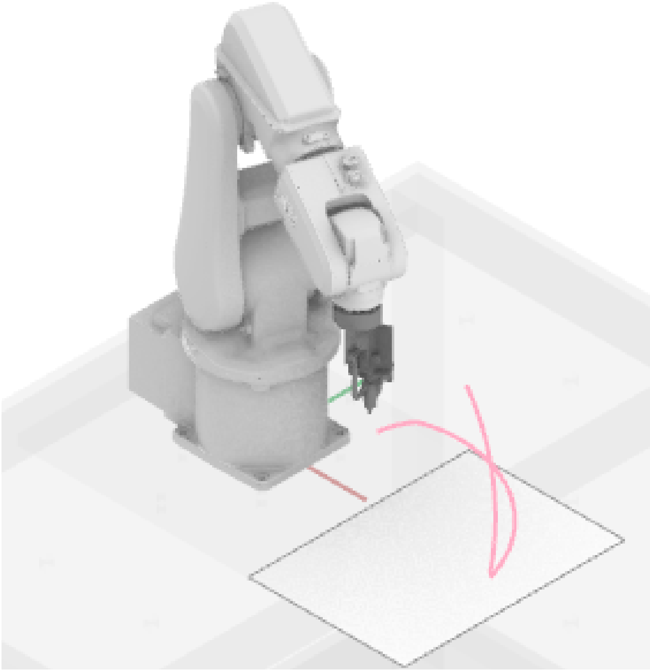


FIG 13 ROBOTIC TOOLPATH TEST

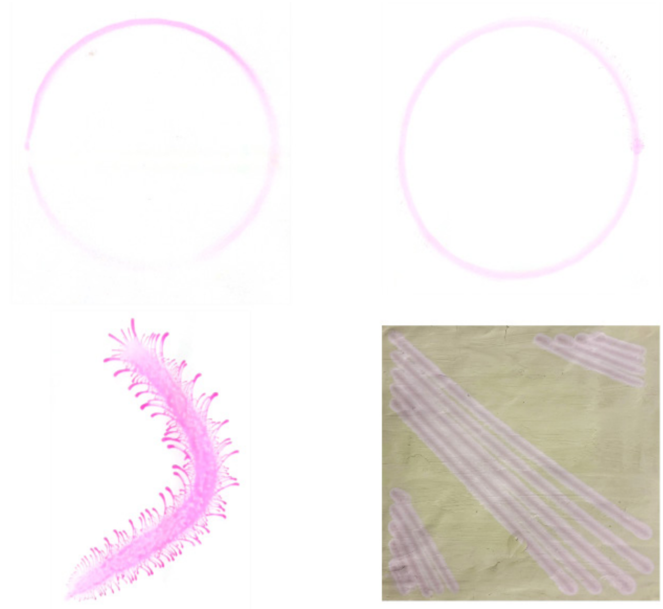


FIG 14. SPRAY TEST

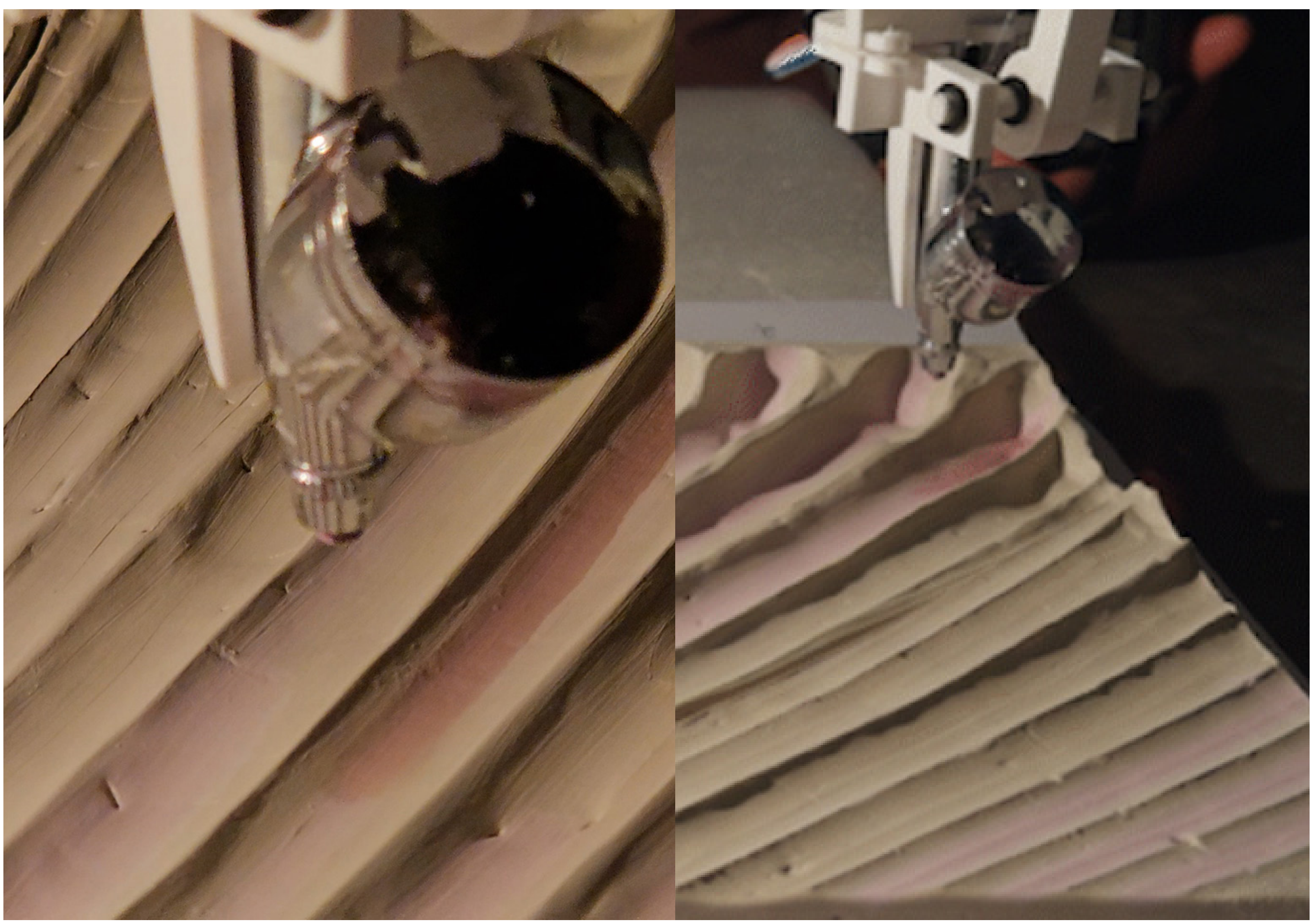


FIG 15 ENGOBE TESTS

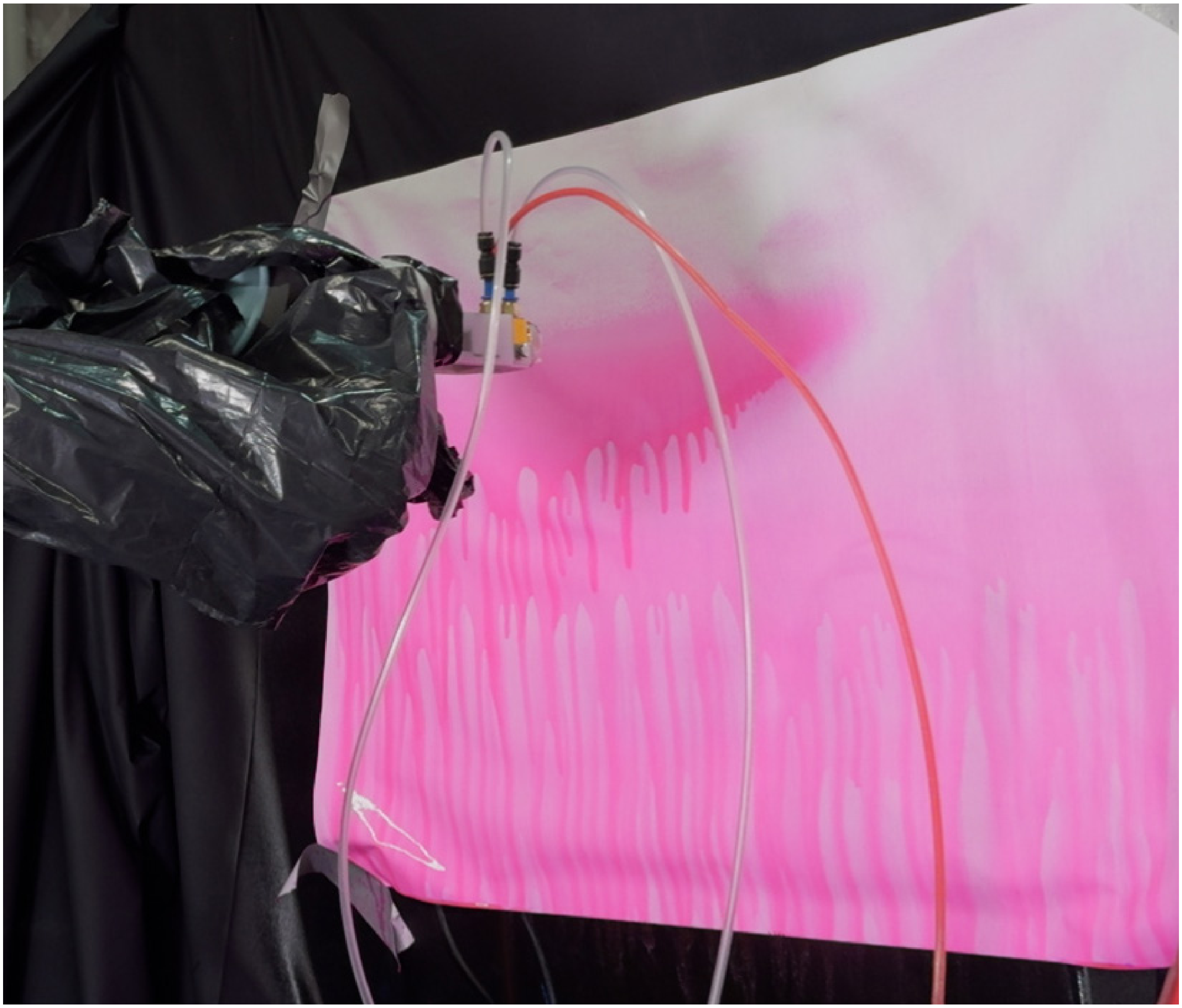


FIG 16 WATER COLOR SPRAY TESTS

With initial tests utilizing the large scale sprayer, a series of toolpaths were generated to start understanding distance, spray angle, material deposition. First with low viscosity liquids and soon thereafter with glazes themselves. Knowing full well that engobe which is made from ceramic grindings could potentially cause the sprayer to clog, we decided to focus on the material property benefits of the glazing itself.

Tests began with a few factors distance, speed, spray angle, toolpath offset, and multi color layering, with a series of flat pre baked ceramic tiles, and a 3D printed piece donated by IAAC. The sprayer was in action, we had to understand how the robot, the glazing and the surface of the sprayed on object would react with different parameters.

As with glazing, the results were not conclusive until the piece was baked as the real color doesnt appear until it glassifies. With more context on baking engobes don't change much from a pre-baked appearance to a post baked , but glazes go through a much harsher chemical process so its color transformation can be quite drastic. With some glazes appearing white pre baked and bright orange on post baked. With this in mind, only powders that showed an initial saturated color were chosen as a way to distinguish between colors and for the possibility of future color prediction between a pre baked piece and a post baked piece. **More on this later.**

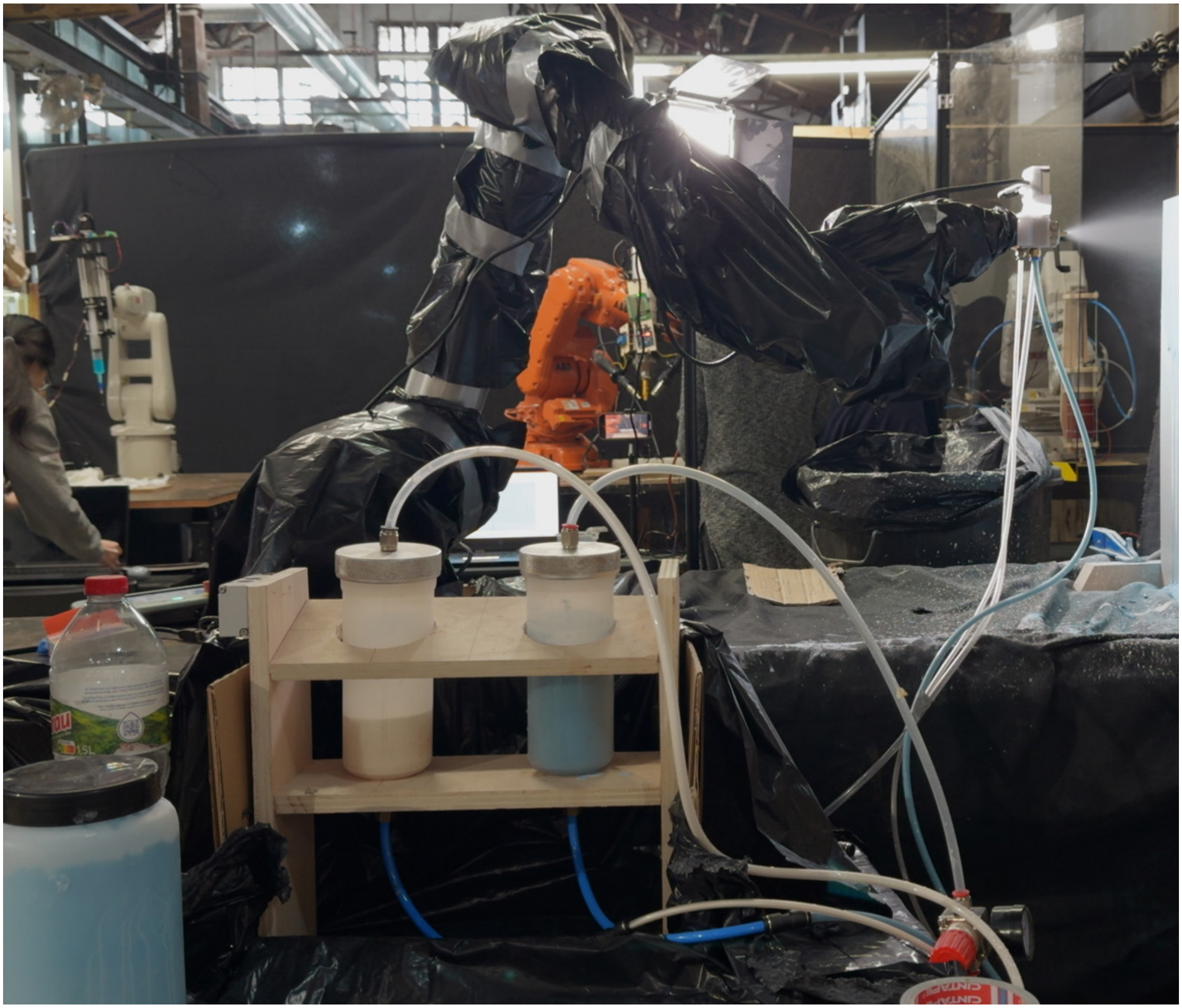


FIG 17. CANISTER SETUP

FIG 18. SPRAY GUN END-EFFECTOR

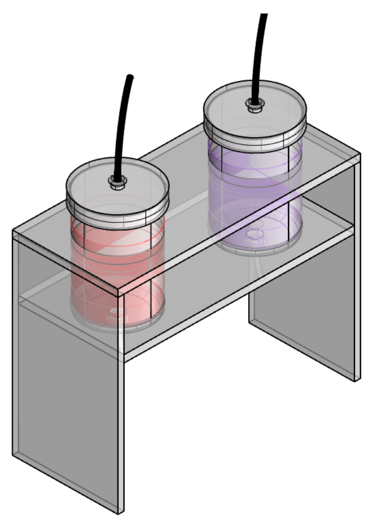
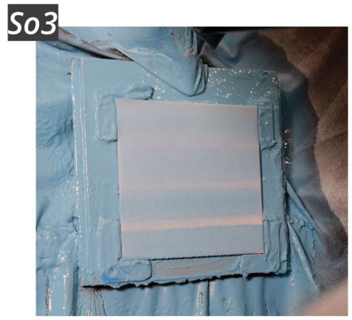


FIG 19. GLAZING CANISTERS

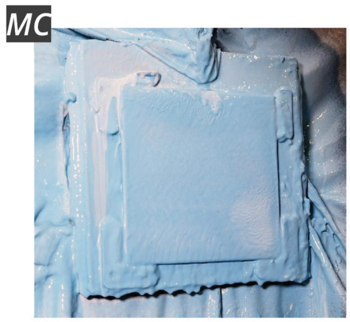
FIG 20. 3D PRINT SPRAY TEST

Distance to Tile:
260mm to 100mm
Steps of 40mm

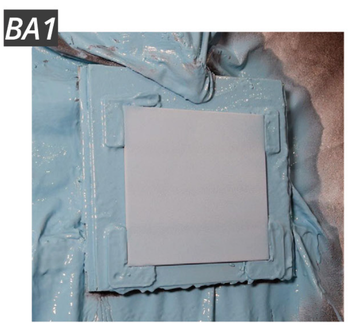


Distance to Tile:
150mm to 50mm
Steps of 25mm

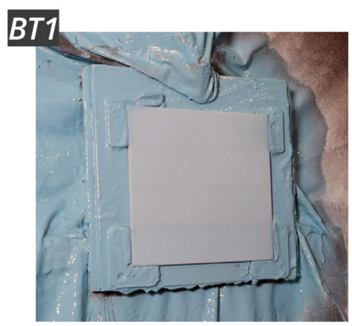
Combination
S5 - +10 per Row
DT2 - Steps of 30mm



S6 in White
Reversed in Blue



Equal Spacing - 50mm
Distance to Piece - 250mm
Five Rows



Equal Spacing - 50mm
Distance to Piece - 200mm

Distance between Lines:
Distance to Piece - 100mm
Spacing +10 each Row

Distance between Lines:
Distance to Piece - 200mm
Spacing +10 each Row

FIG 21 Variation Tests

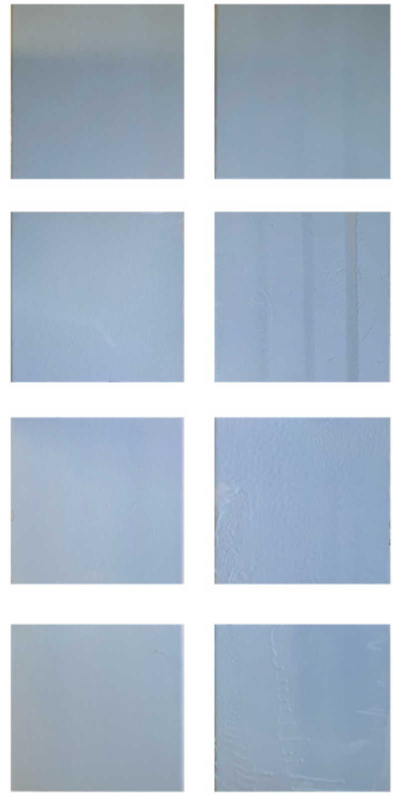


FIG 21. Pre-Baked

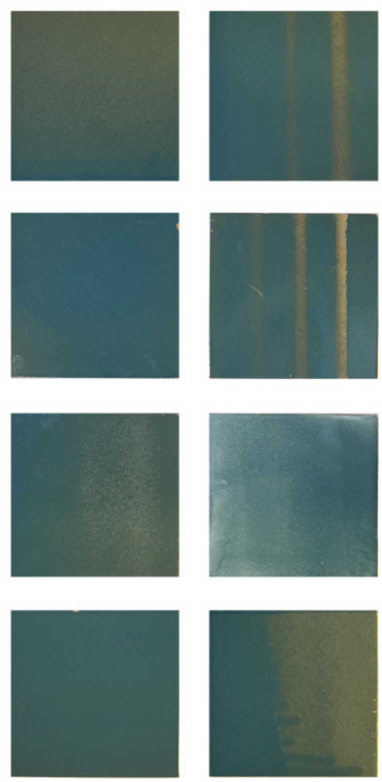


FIG 22. Post-Baked

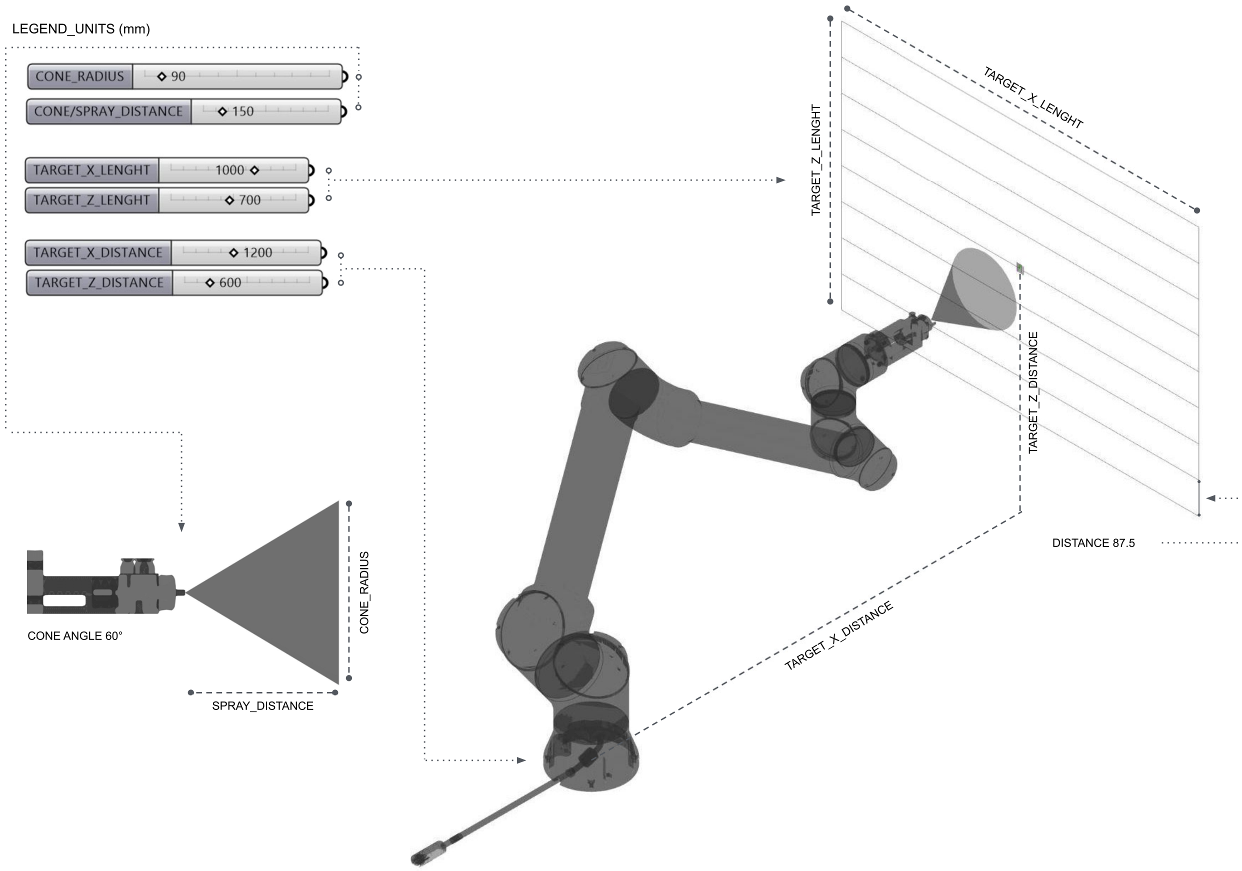


FIG 23. Toolpath Initial Parameters

Precise Robotic Glazing

Precision Robotic Glazing (PRG) is a process that involves pre-programming robots to create toolpaths for glazing and finishing digitally designed objects. The goal is to enhance the workflow of digital artists by integrating robotic fabrication capabilities into existing design tools, such as Rhino Grasshopper, used for modeling and 3D printing.

This approach is particularly relevant for large studios like Studio RAP, which currently design their facades digitally and use robots for 3D printing but rely on artisans for spray glazing. While this method worksfor the Ceramic House, which used a single color, it becomes increasingly challenging for the artisan to accurately depict complex color transitions, gradients, and textures as the complexity and quantity of parts increase.

To test the PRG concept, we created an assembly of two towers, each consisting of five 3D printed bricks. The bricks featured varying textures on one side, numbers for identification, and slots for assembly and glazing. When stacked together, the bricks formed a holistic image, but each brick was glazed individually.

We explored four different glazing techniques:

1. Multicolor piece: Applying multiple colors to a single brick.
2. Fine line detailing: Creating intricate line patterns through precise glazing.
3. Layering: Reducing 3D printing artifacts and creating texture through layered glazing.
4. Color gradient: Achieving smooth color transitions across multiple bricks.

The entire design process, including discretization into individual pieces and embedding of toolpaths, was performed within Grasshopper. This approach has the advantage of embedding color information and creation instructions directly into the digital model

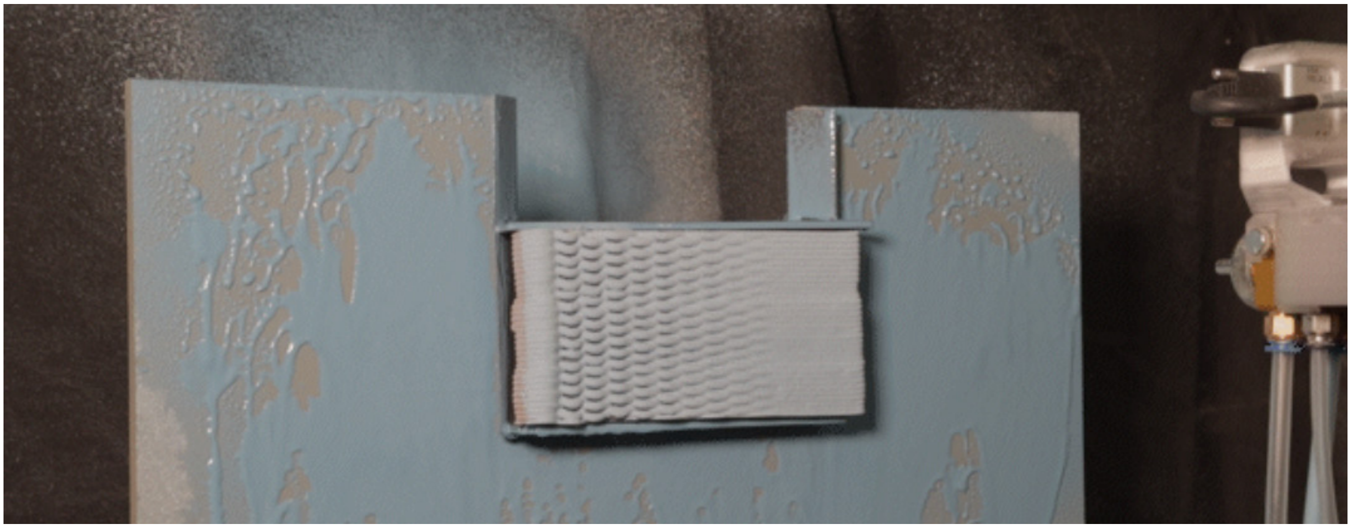


FIG 24. Single Color

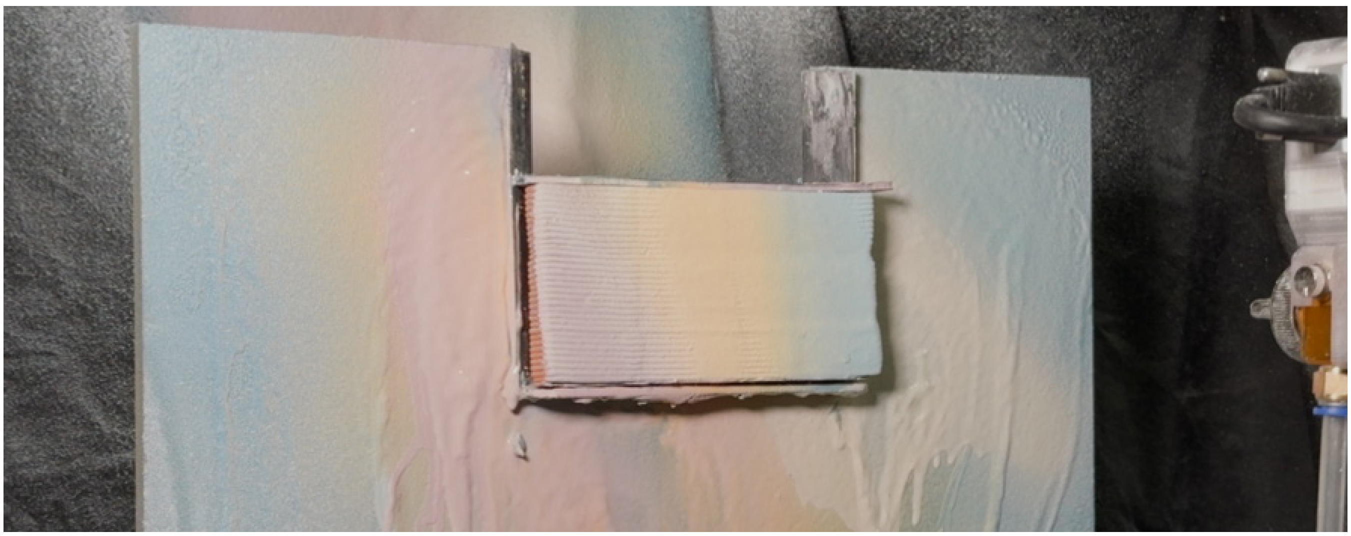


FIG 25. Multi-Color Test


FIG 26. Fine Detailing

FIG 27. Post-Baking (KILN Variance)

Understanding the positioning of pieces inside the kiln is rather an interesting problem to tackle at in later stages, due to the kilns non uniform heating a piece could act rather differently from its proximity to where the main heat source is entering. Over-Burning of the pieces to incompatible clay can all be problems once setting the adequate environment. Low temperature glazes to high temperature glazes also have different times of baking as the ramping of temperatures in the kiln is also of significant importance. (FIG 27-34)

With the following tests a level of control was achieved and thus determining what scope of work can be done at the IAAC facilities. Due to a constraint of pressure a future improvement could be to utilize a digital pressure regulator as the pressure remained a big issue throughout. (Fig 28-

With the final masterclass we aimed for, a four way gradient. We took two handmade fluted clay pieces, which we decided to glaze with a strong angle to only be bale to see two colors at once. We did a gradient from Yellow to orange and on the other side of the flute we went from blue to purple.

When attempting to 3D print pieces and go through a process of drying for an initial bake, the robotic glazing timing and a second fire to glassify the actual glaze the time became too much and the idea of facade scale was scrapped with the remaining time left, although with enough budget a more controlled environment, access to a closer kiln, the project should be continued.

Luckily for us a series of 3D Printed pieces would be donated to test on. Without Francisco (Paco) Martinez a big portion of this project would be in the what-if department.

Trying to bring more control to the spraying in non-planar geometry, a test to create a two-way gradient while attempting to layer the colors and blend was done.

FIG 28 Valdaurra Kiln

FIG 29 Glazing Issues

FIG 30 Gradient Tower

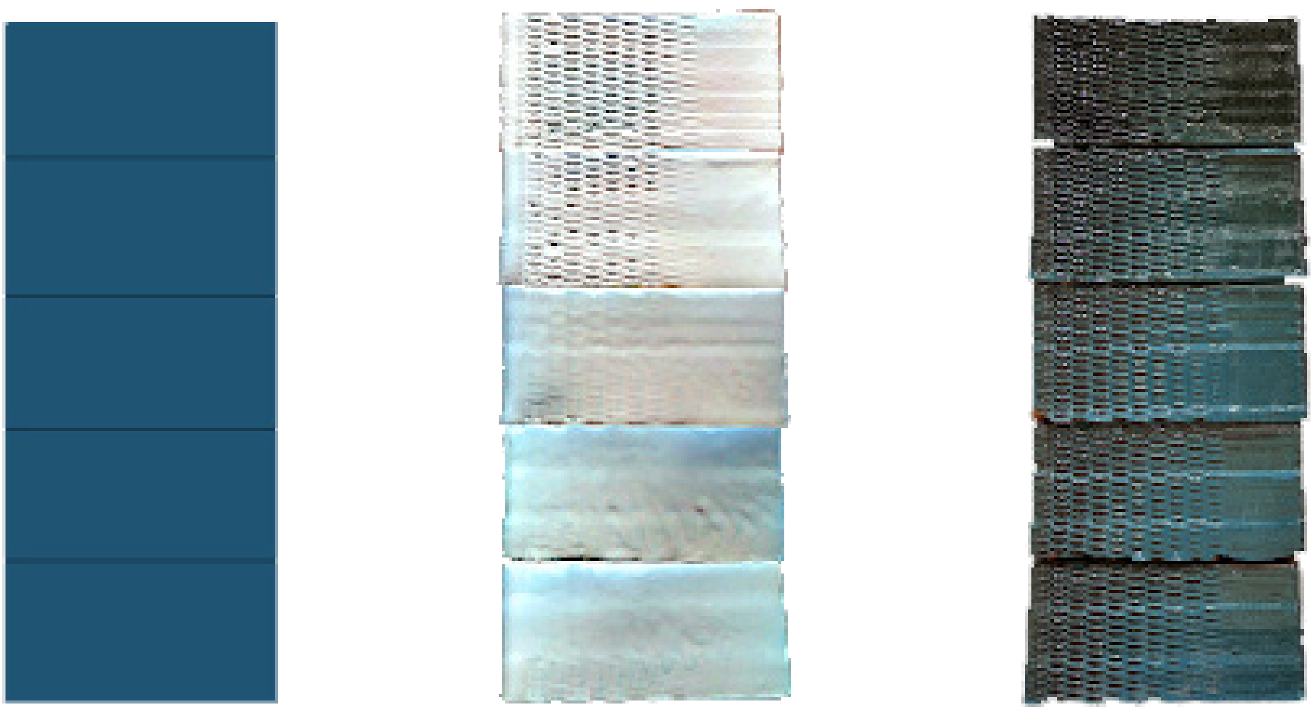


FIG 31 Solid Color Tower

FIG 32 Gradient Tower

FIG 33 Multi-Color Tower

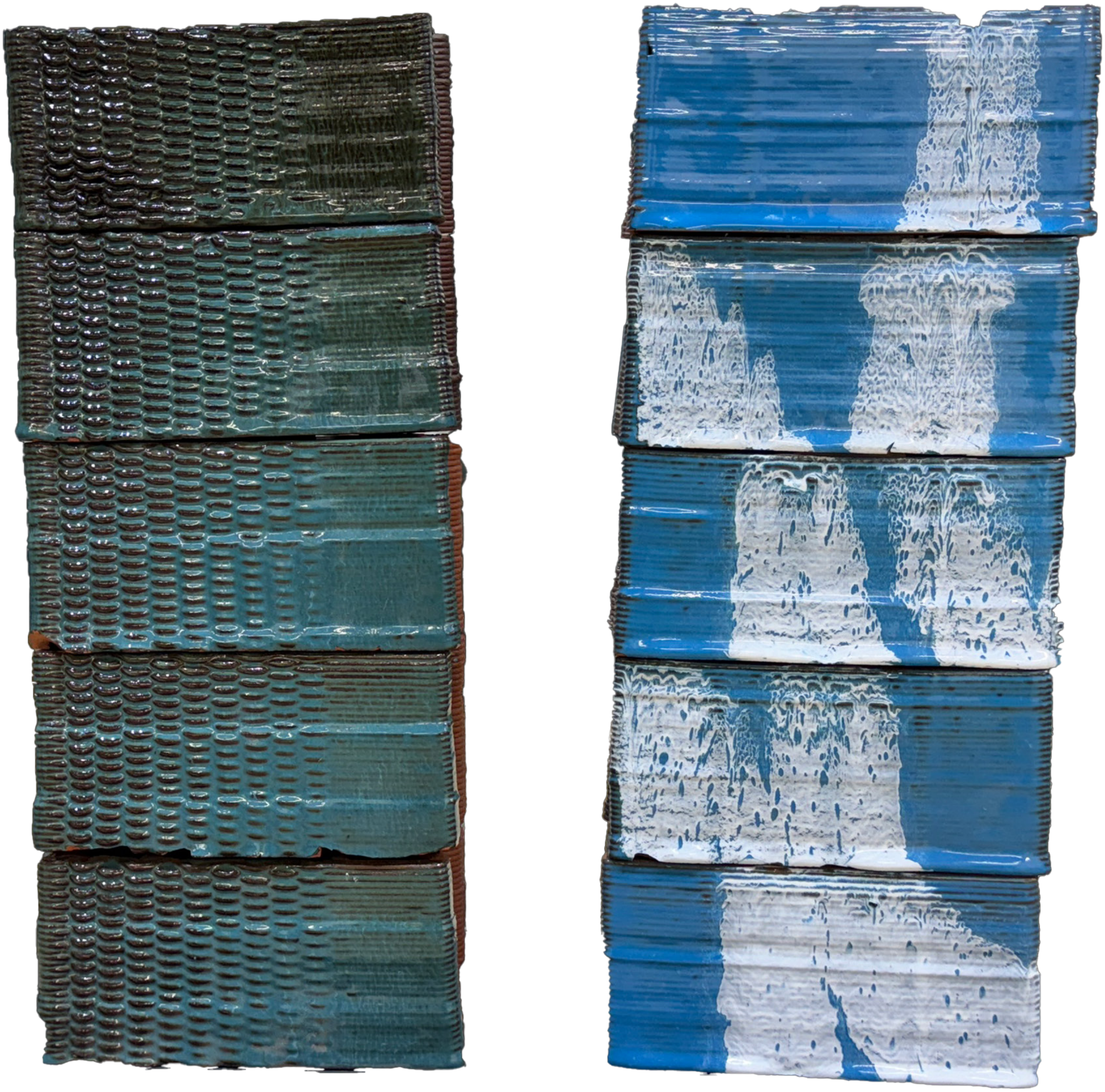
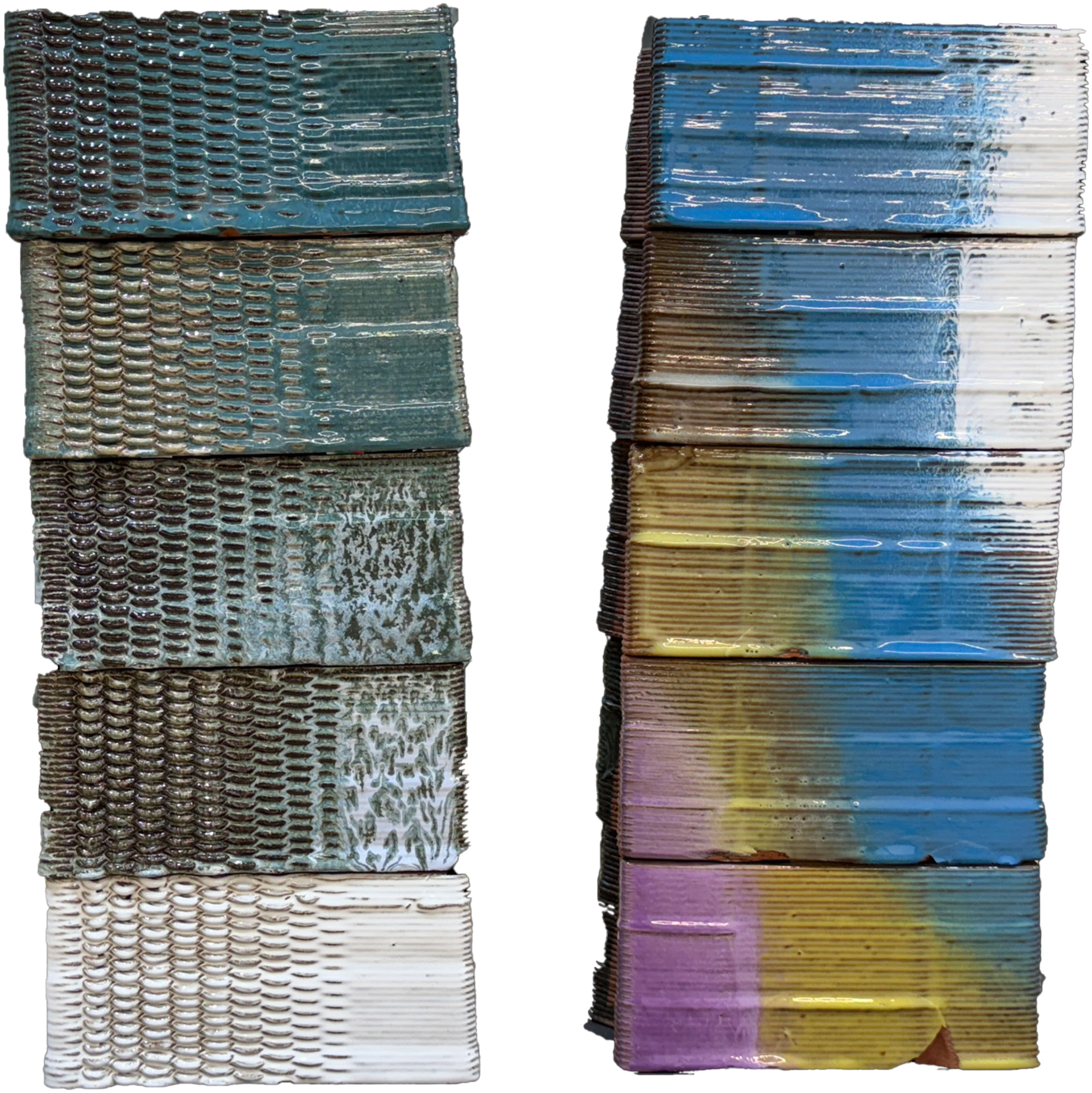


FIG 34 Printed Towers



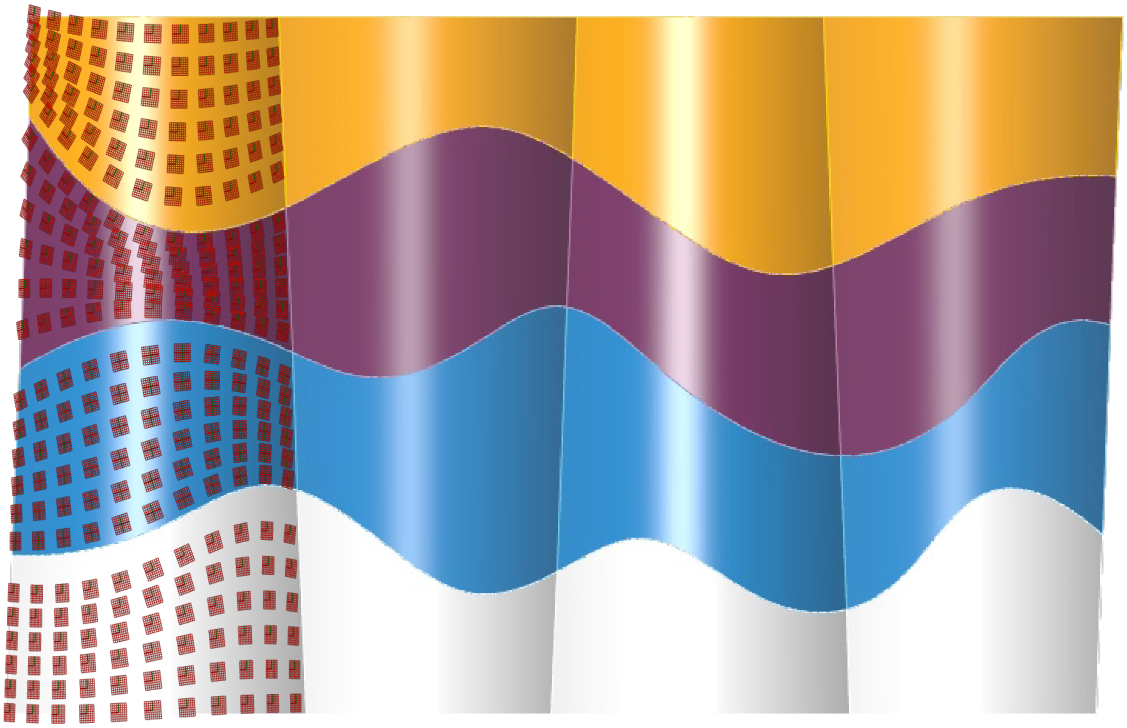


FIG 35 Renderised Roof Tile

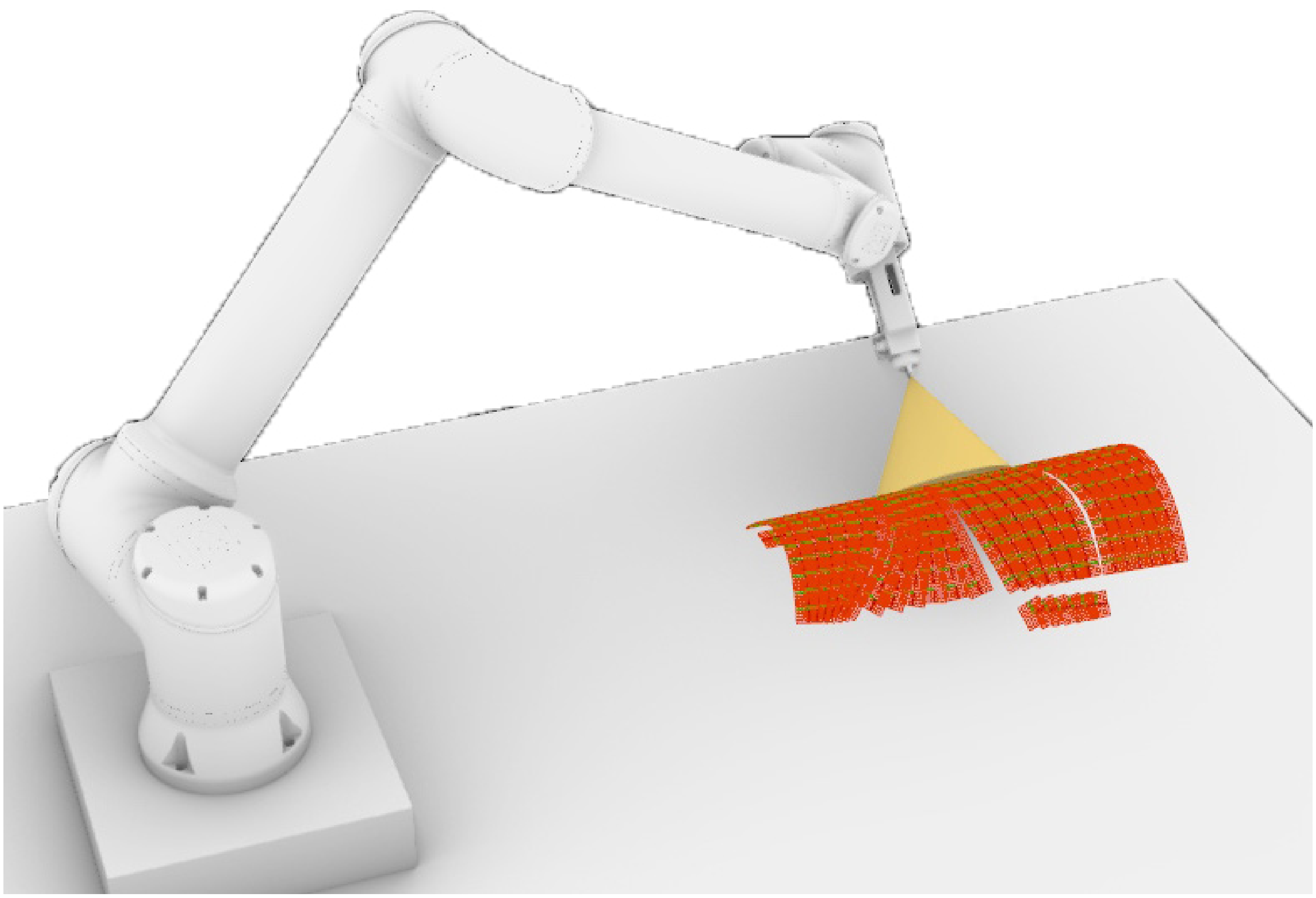


FIG 36 Robotic Toolpath

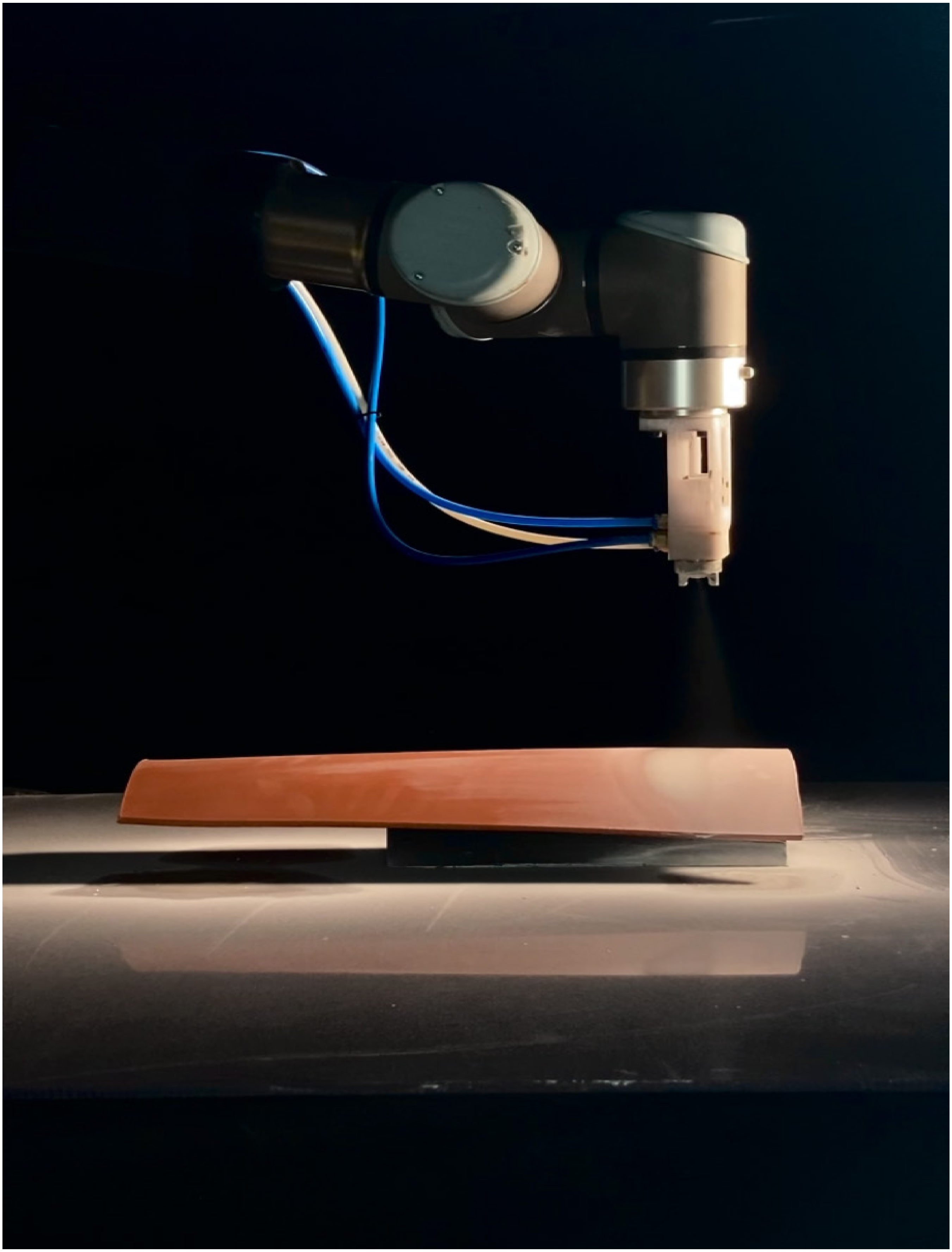


FIG 37 Robotic Test on Roof Tile

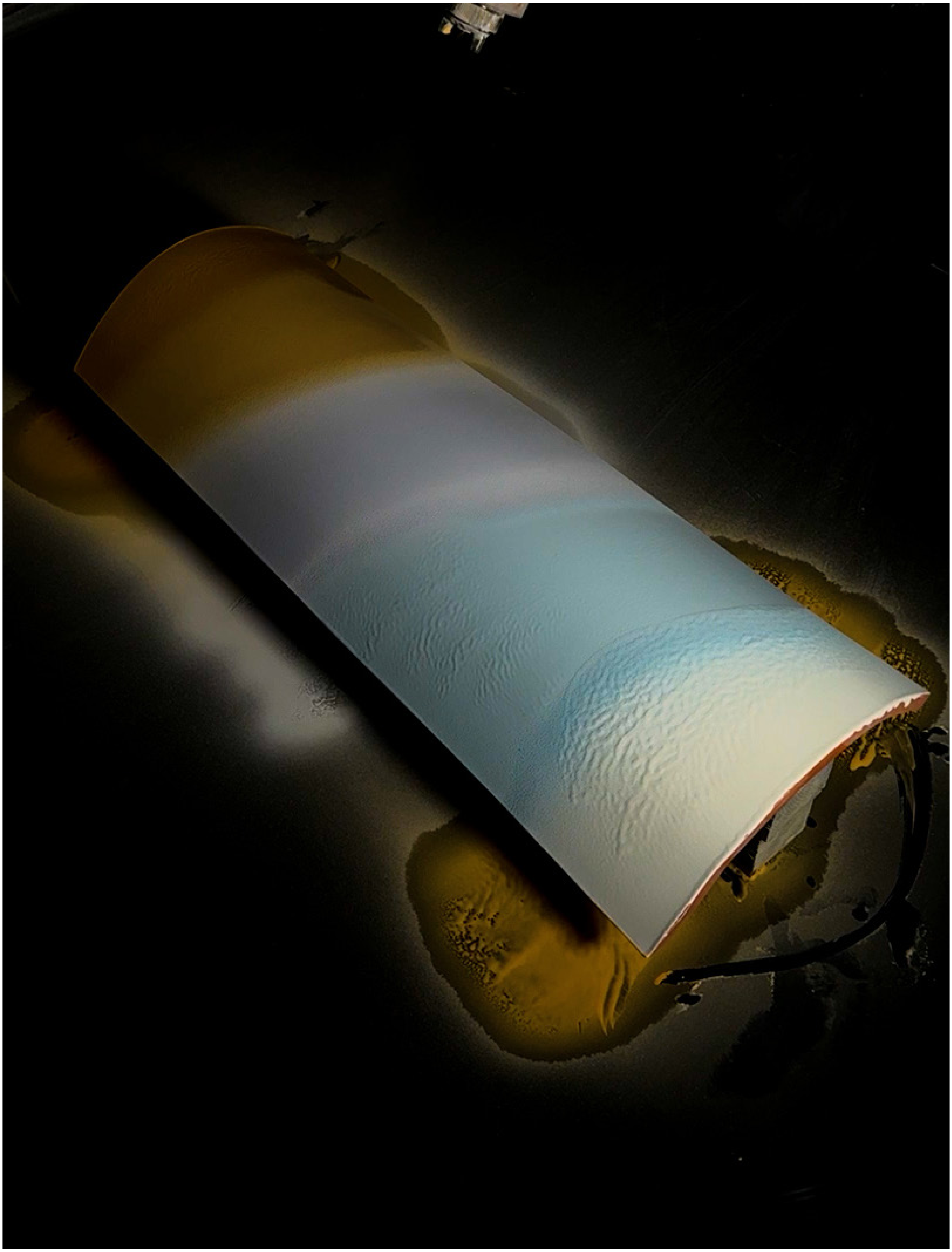


FIG 38 Glazing on Roof Tile

FIG 39 Post Baked Roof Tile

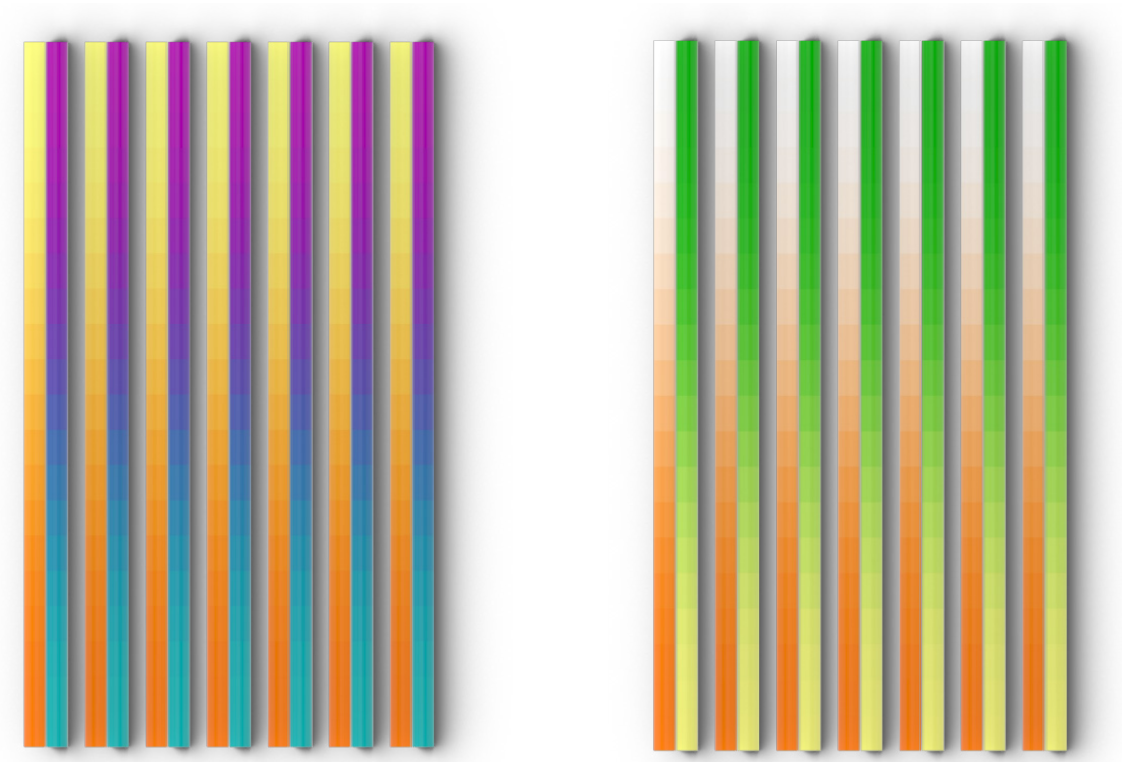


FIG 40 Ondulating Ceramic Renders

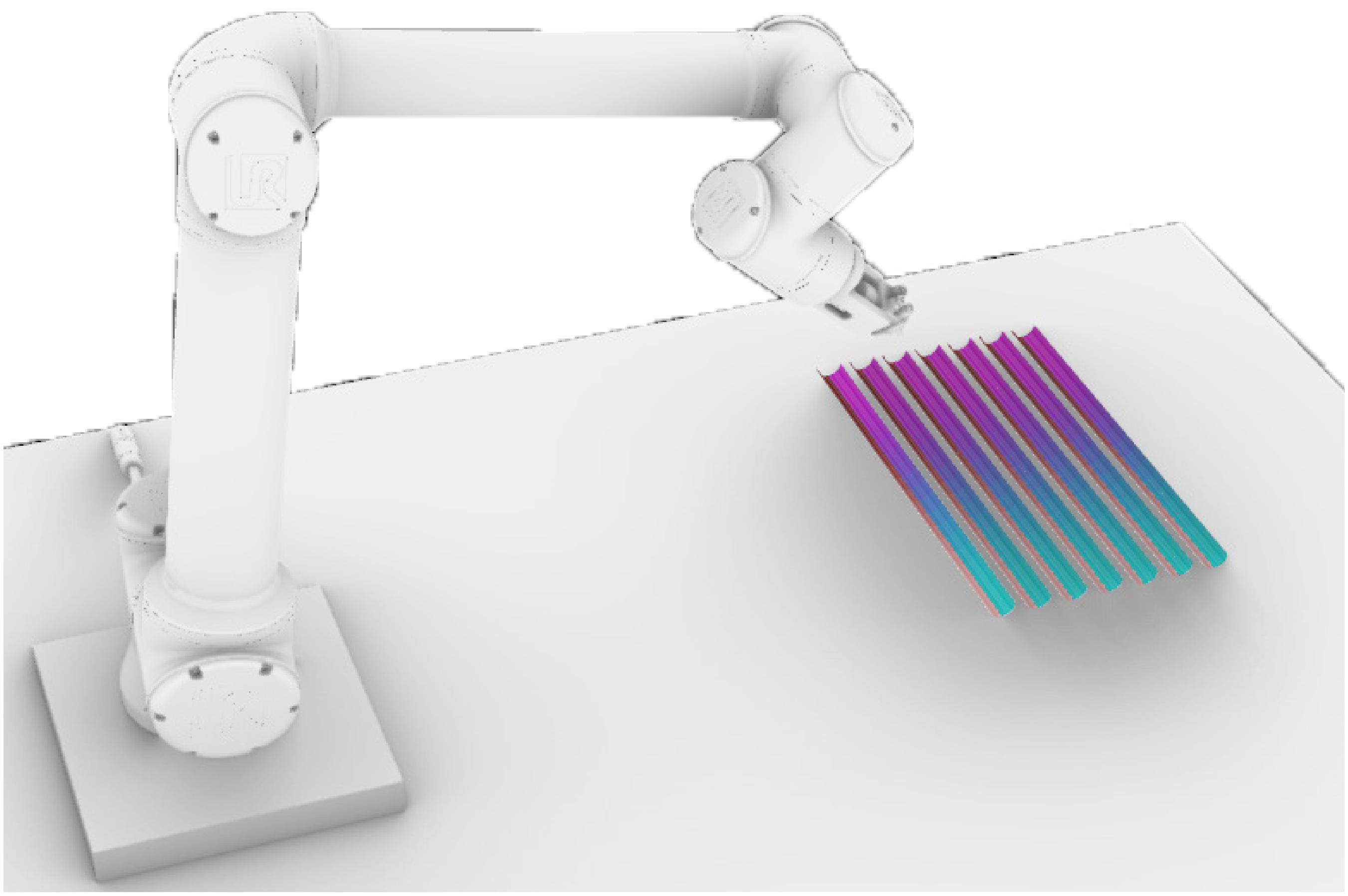


FIG 41 Ondulating Toolpath

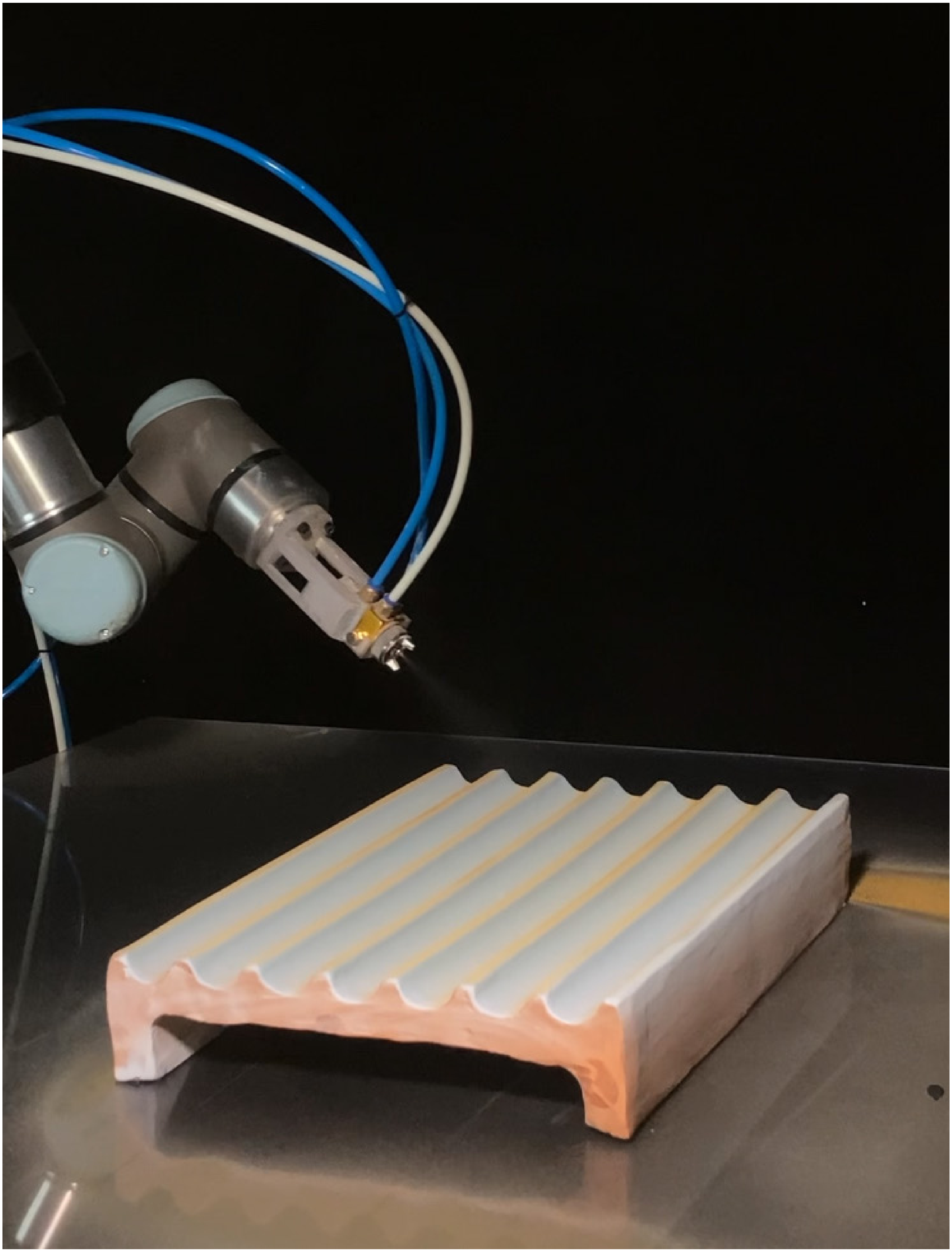


FIG 42 Ondulating Spraying

FIG 43 Ondulating Final Piece 1

FIG 44 Ondulating Final Piece 2

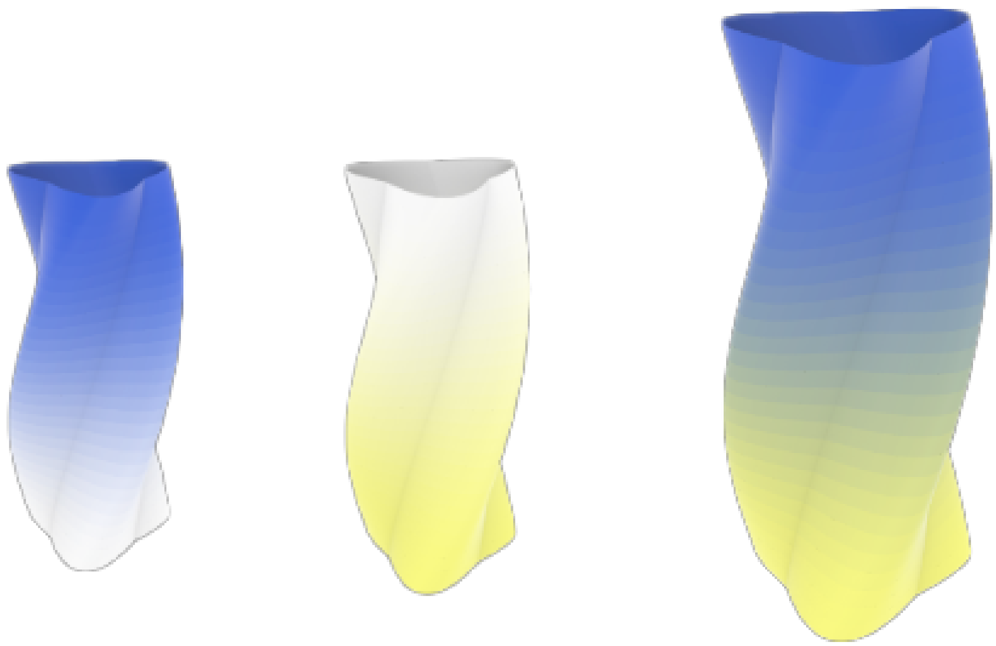


FIG 44 Francisco (Paco) Martinez Vase

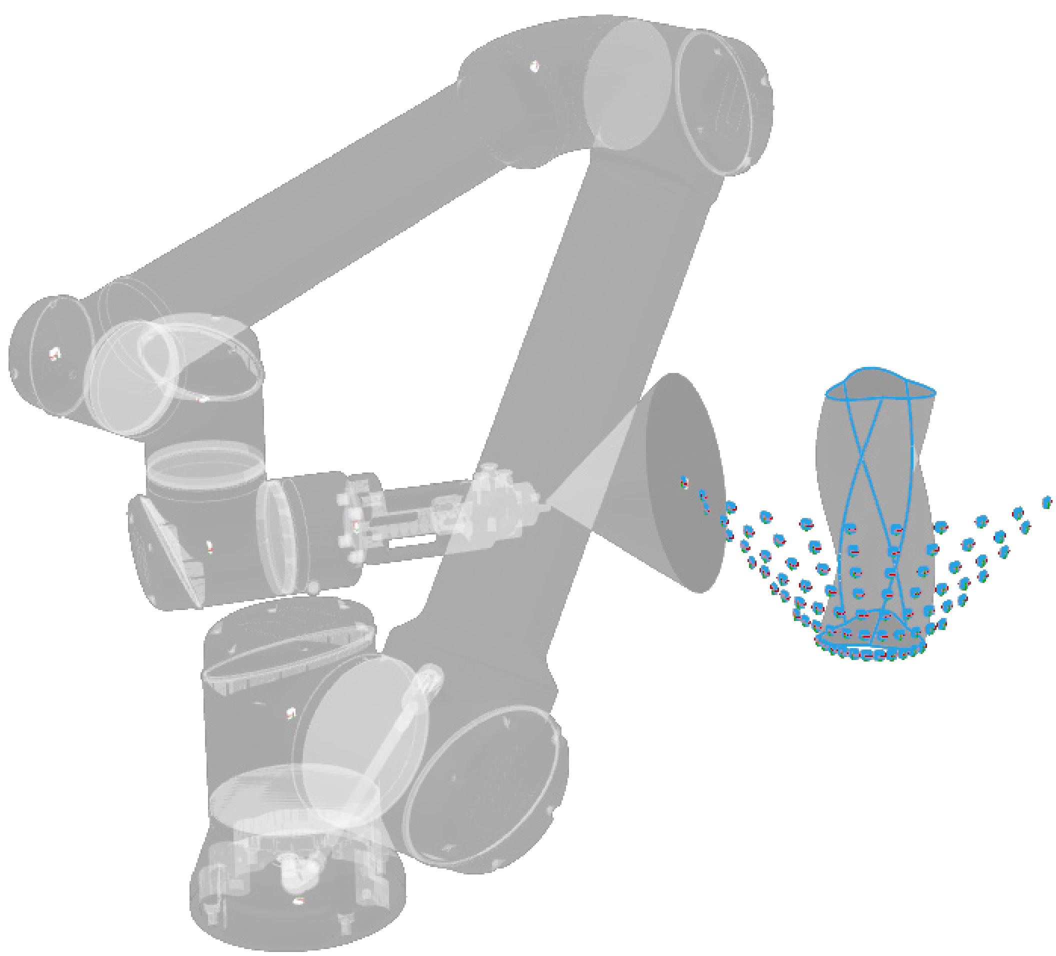


FIG 45 Francisco (Paco) Martinez Vase Toolpath

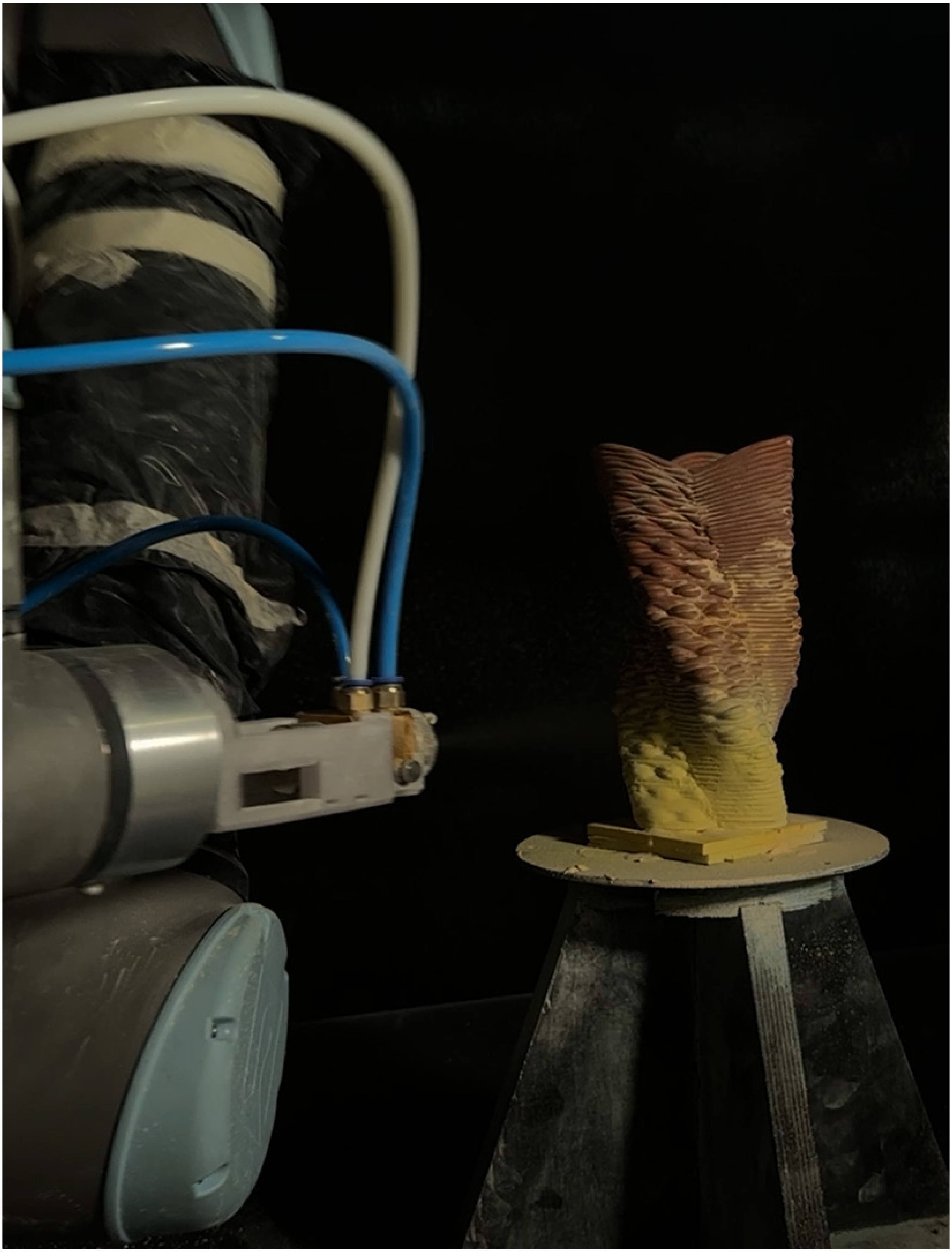


FIG 46 Francisco (Paco) Martinez Vase Spraying (Layering+Gradient)

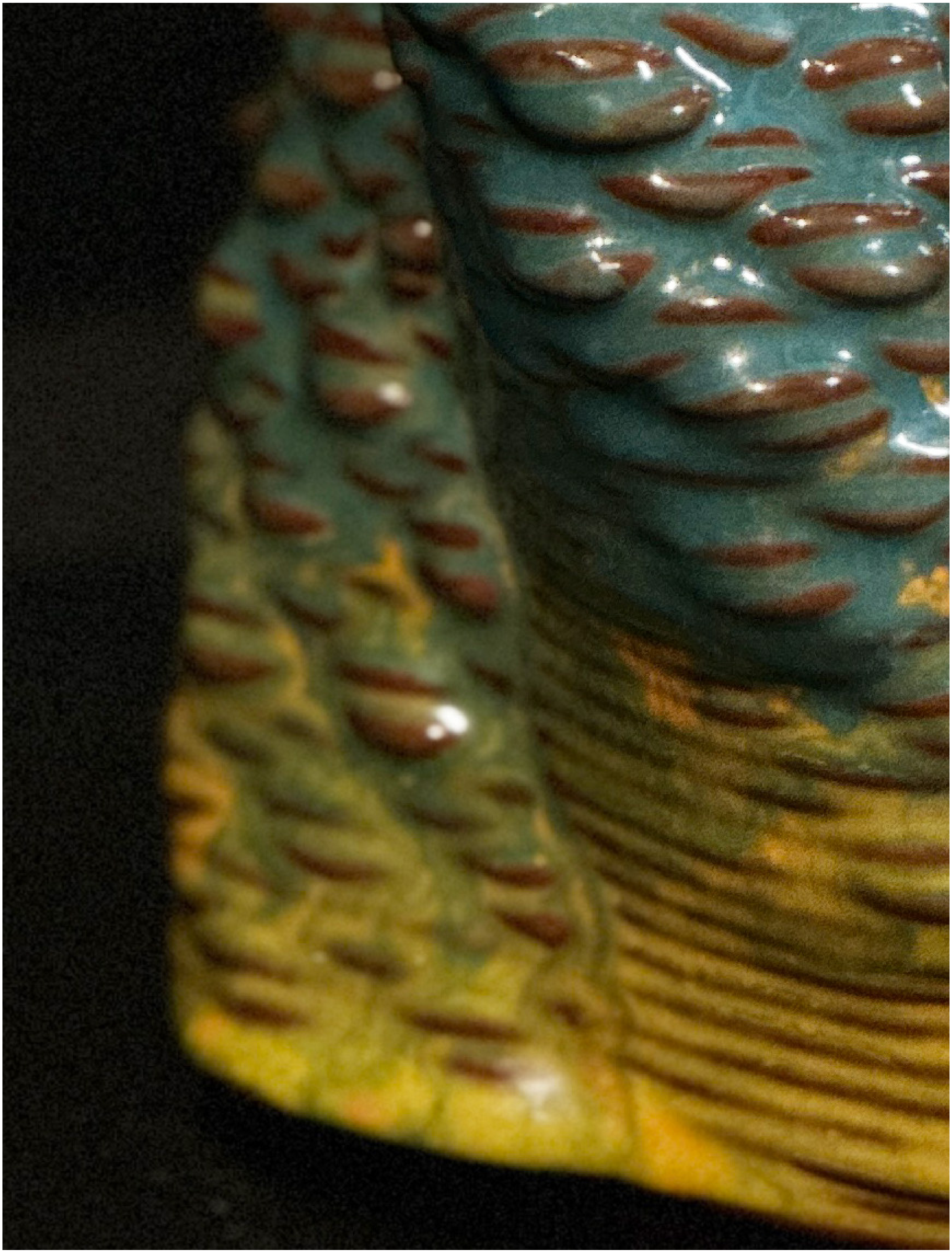
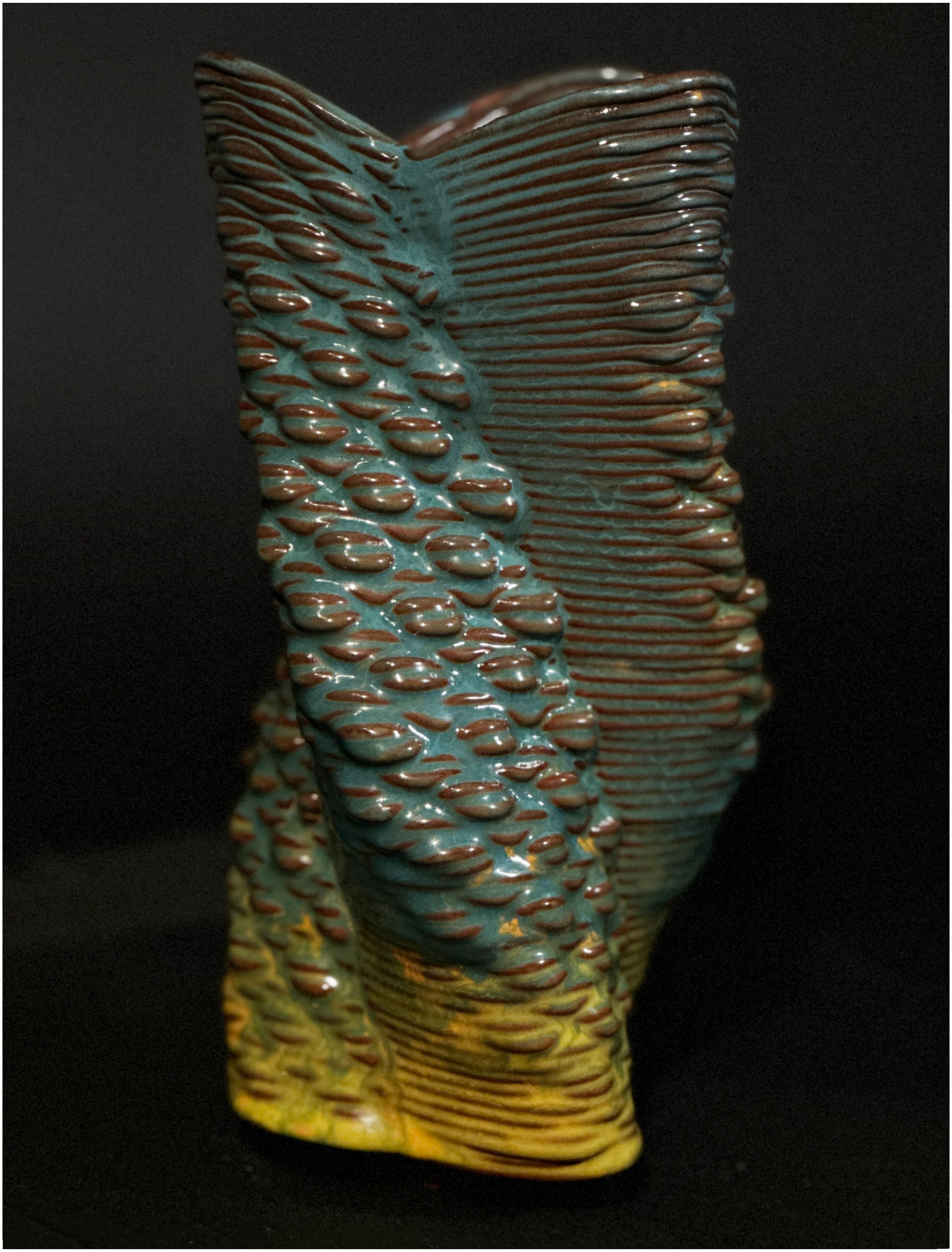


FIG 47 Francisco (Paco) Martinez Vase Baked Sculpture



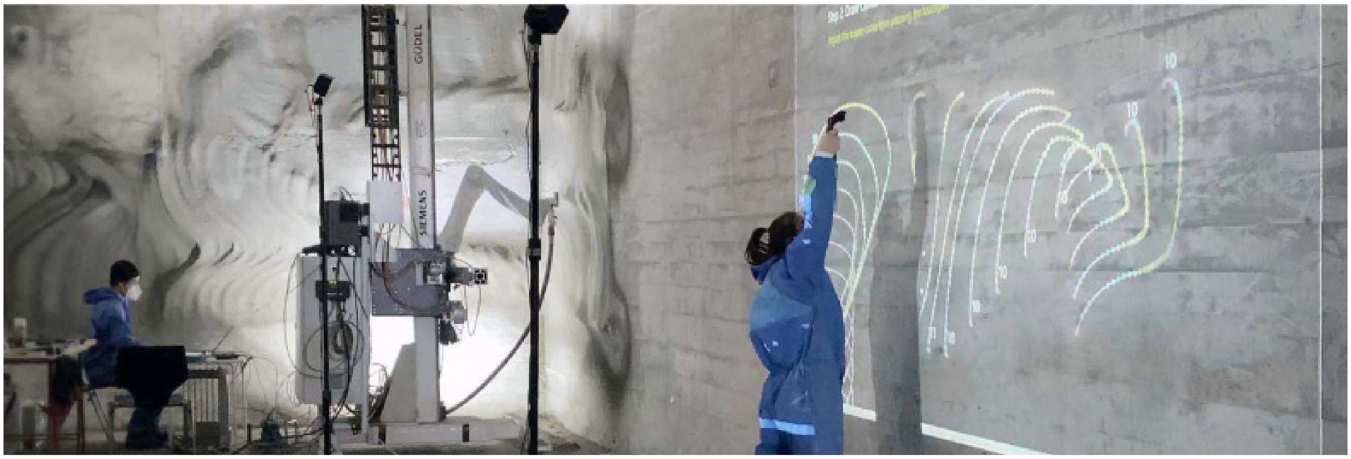


FIG 49 Daniella Mitterberg - Interactive Robotic Plastering

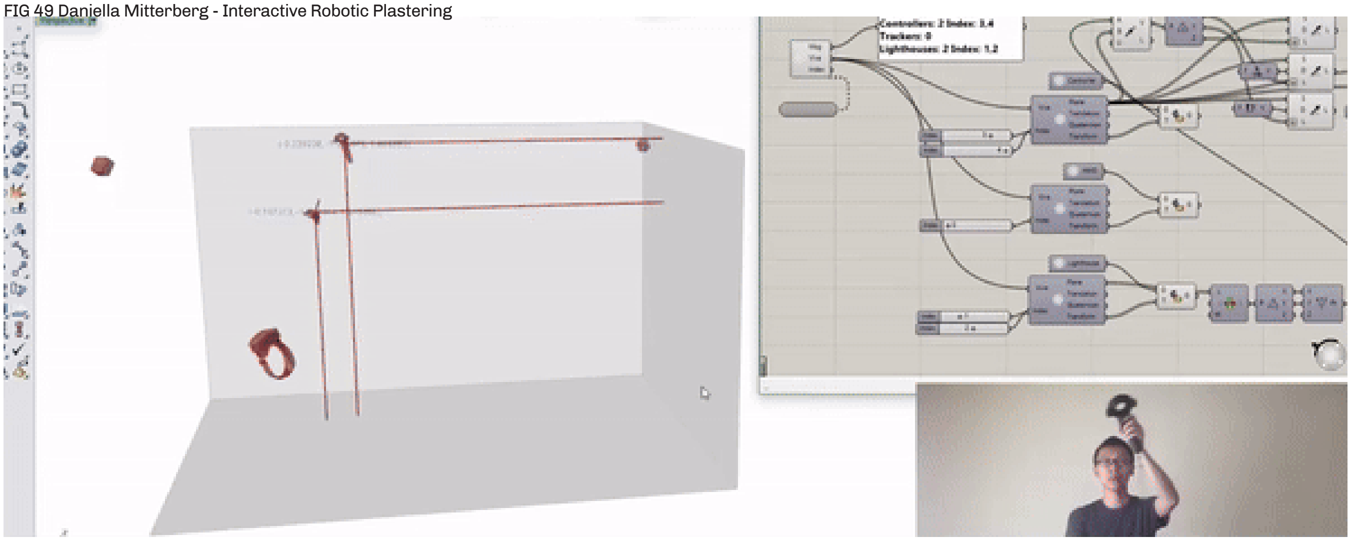


FIG 50 GITHUB REPOSITORY HTTPS://GITHUB.COM/CCC159/VIVETRACK

Human-Machine Collaboration

As a further exploration in an attempt to teach a robot how to effectively create a more fluid stroke, and combine a much finer synergy between how a craftsman may spray by hand and its robotic counterpart, a Human-Machine approach was derived.

With VR equipment accessible to us we began explorations following on the footsteps of various projects that had utilized a workflow that could be deemed similar. In the paper "Interactive Robotic Plastering: Augmented Interactive Design and Fabrication for On-site Robotic Plastering" Daniela Mitterberg and ETH Team utilized ROS to localize the HTC VIVE Conbtroller in space and thus were creating an adaptive robotic toolpath for spraying plaster in-situ. (FIG.)

As a different approach our team found a GitHub repository that undertook the task of being able to stream the live data (Positioning) of HTC VIVE devices directly onto Grasshopper. This approach proved to be quite a powerful tool to add to our arsenal, albeith it only worked in RHINO6. To correctly track the trackers, a space surrounding the robot UR10e ,two Lighthouses would be placed that would have a fixed position, as well as having the headset in view of the Lighthouses, this would allow for the tolerance of transformations to diminish, the more devices that are located in the space, the more accurate the tracking becomes.(FIG.)

To further customize the plugin "VIVETRACK", we developed custom PYTHON Scripts that would RECORD the current plane of the tracker itself in space and reorient based on a custom made Human-USE end-effector. Velocities and when the human activated the spray were also recorded; this end-effector would allow for a case study in which invited ceramicists from KEMA Ceramics in Barcelona, Spain to partake on a data recording session where the artist would have their movements mimicked by the robotic arm. The following images were the results. (FIG 53-63)

FIG 50 Test on HTC VIVE

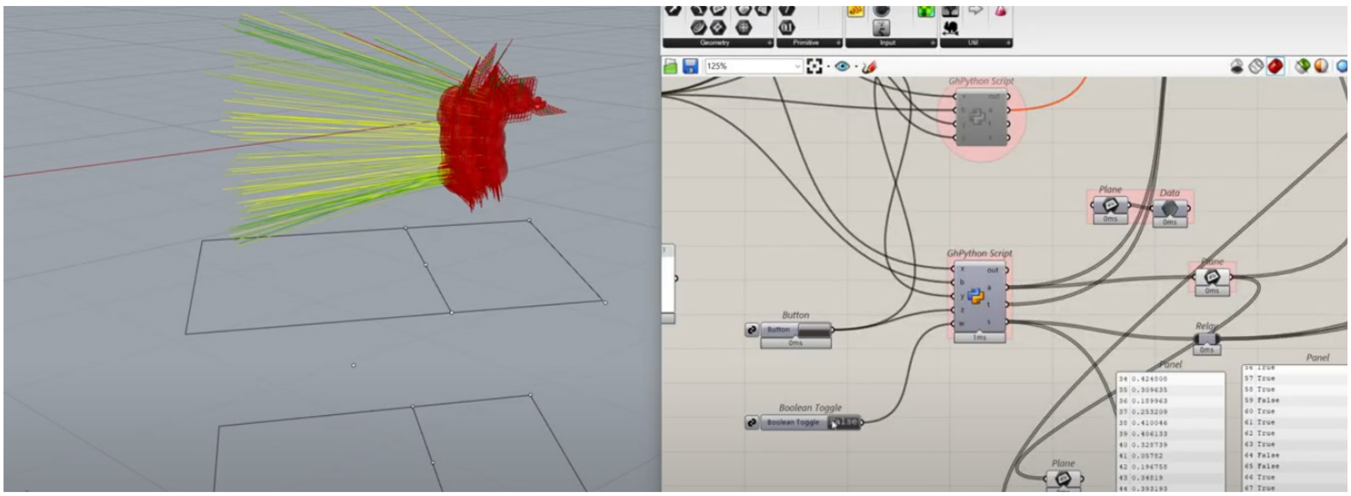


FIG 51 GH Plane Recording

A. HTC Vive Lighthouse 1+2
B. HTC Controller
C. HTC Headset
D. UR10e w/Spray End-Effector
E. MQTT Publishing Computer
F. HTC Receiving Computer/Toolpathing
G. Custom Spray Gun End-Effector
H. Glazing Canisters
I. Spray Piece

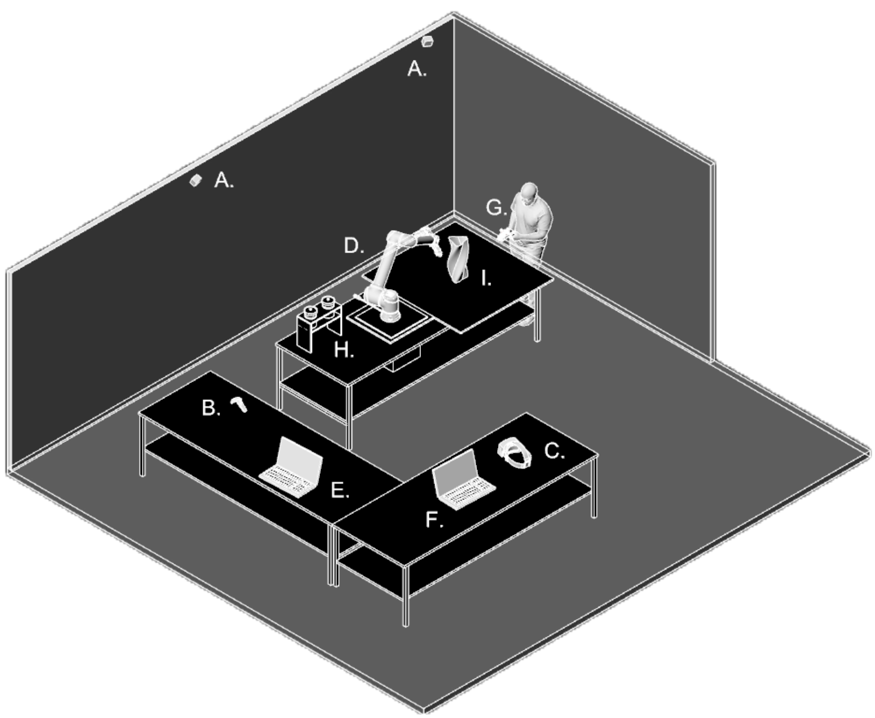


FIG 52 UR10e Robotic Cell

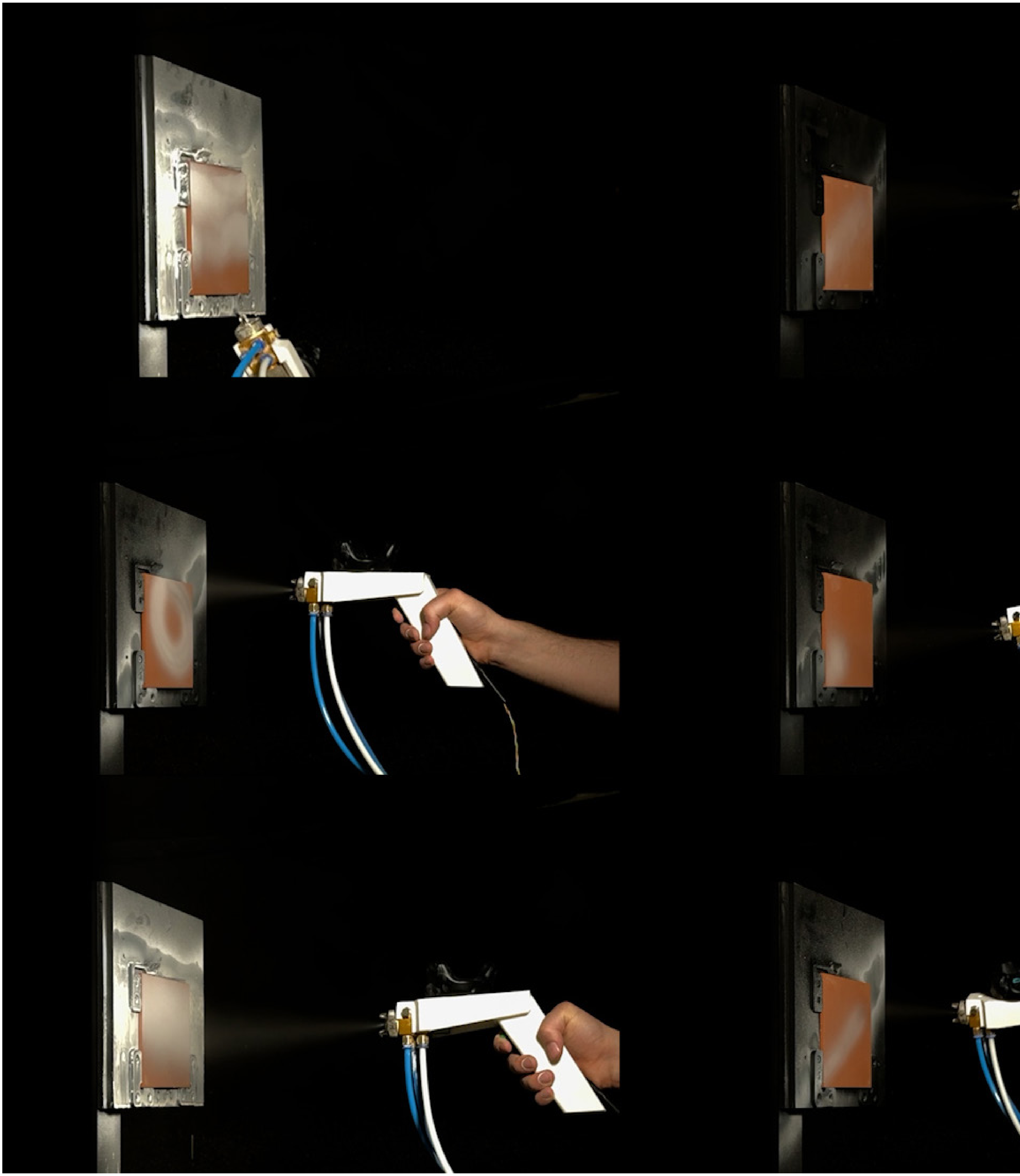
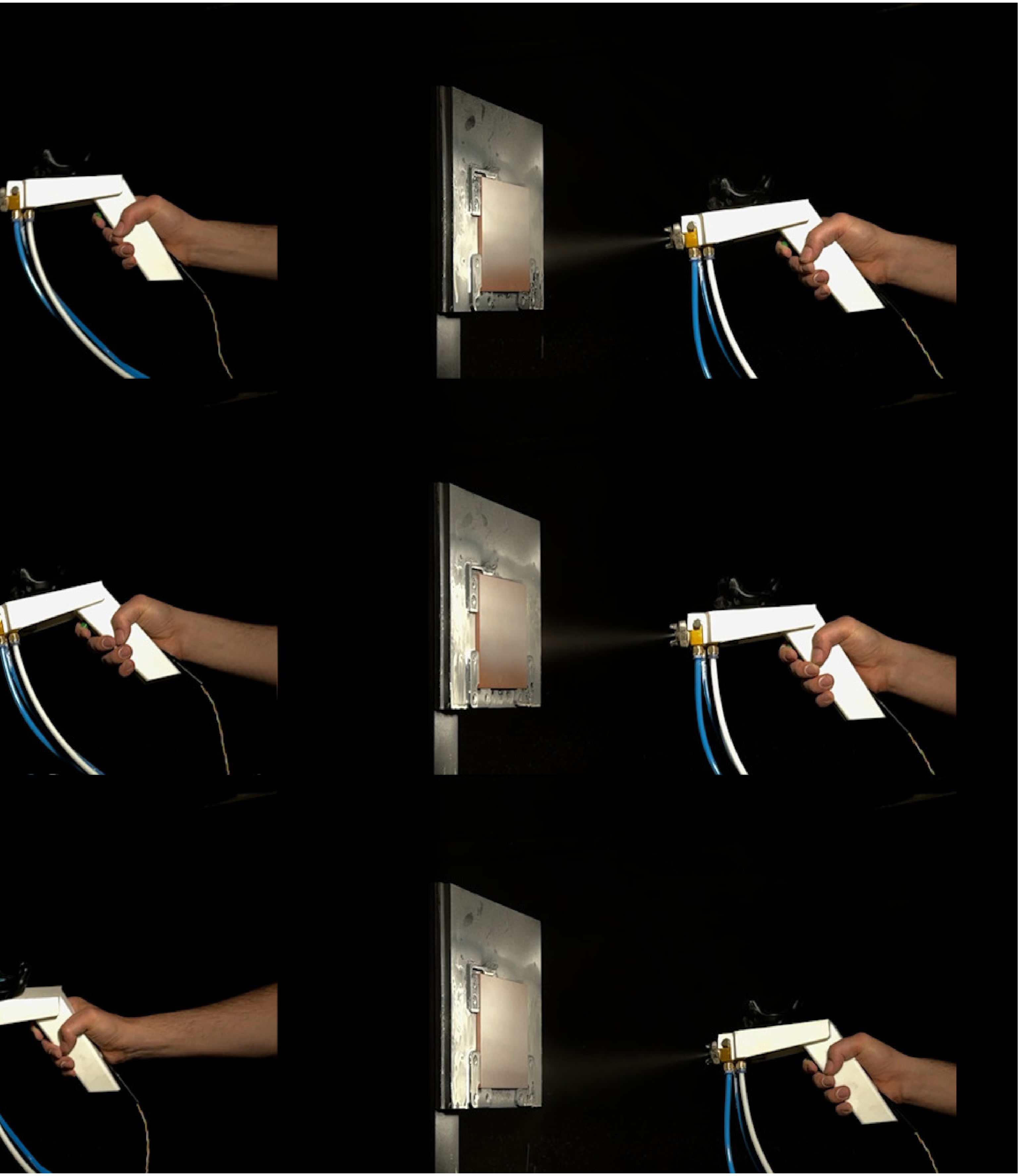


FIG 53 Variance Tests/Data Recording



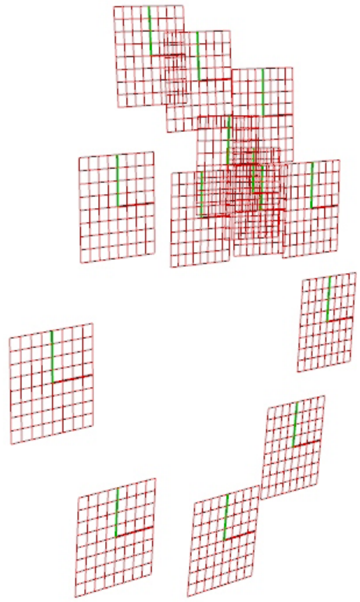


FIG 54 Planes Circle GH Recording

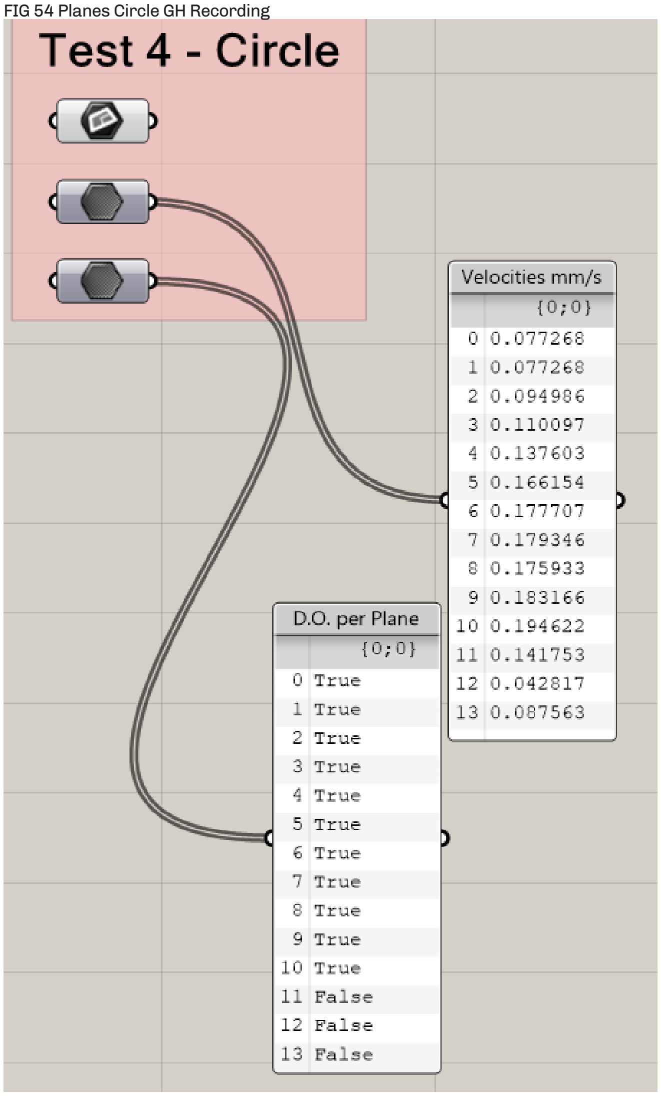
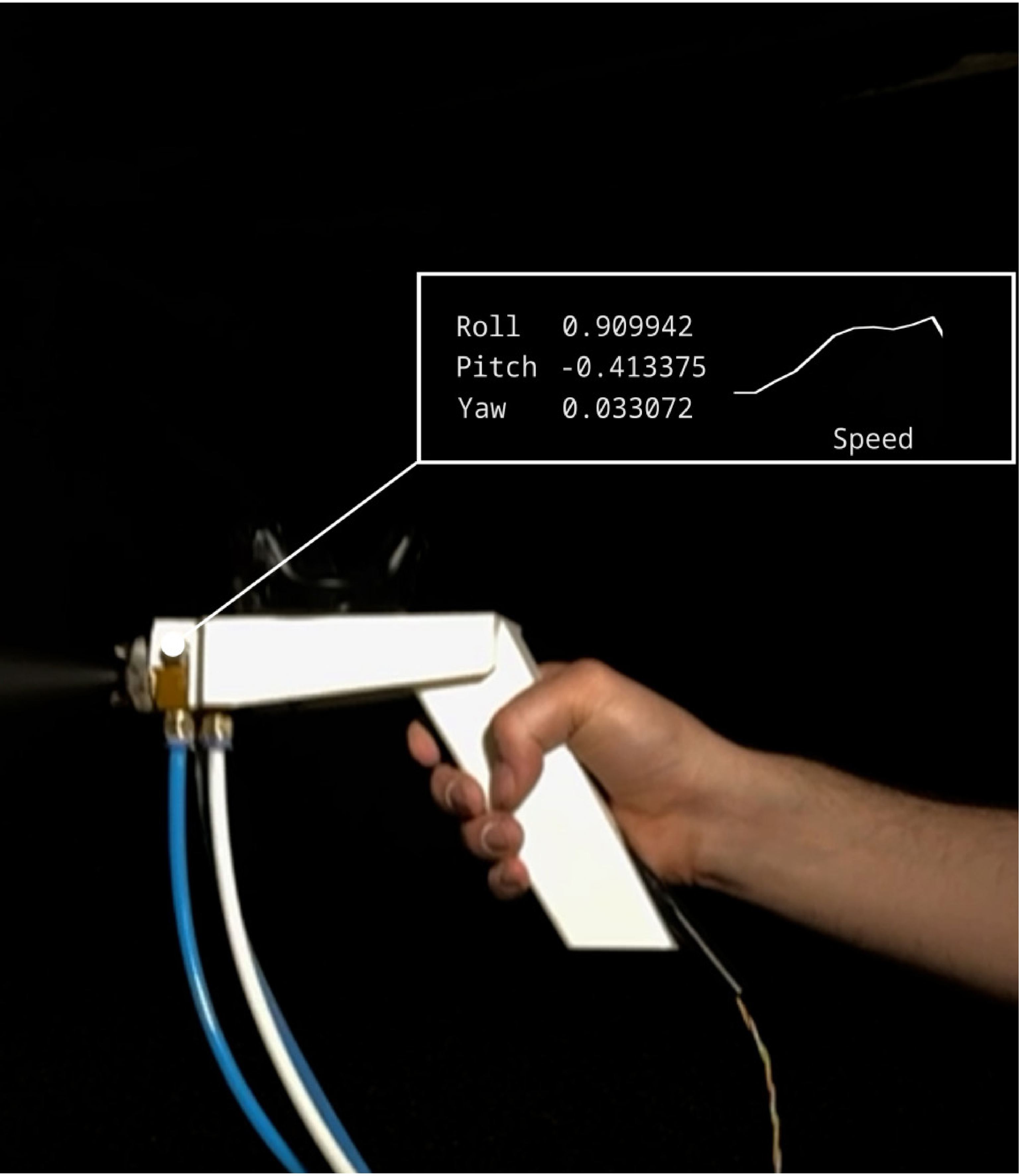


FIG 55 Speeds/Digital Outputs

FIG 56 Roll Pitch Yaw


Roll 0.909942
Pitch -0.413375
Yaw 0.033072
Speed

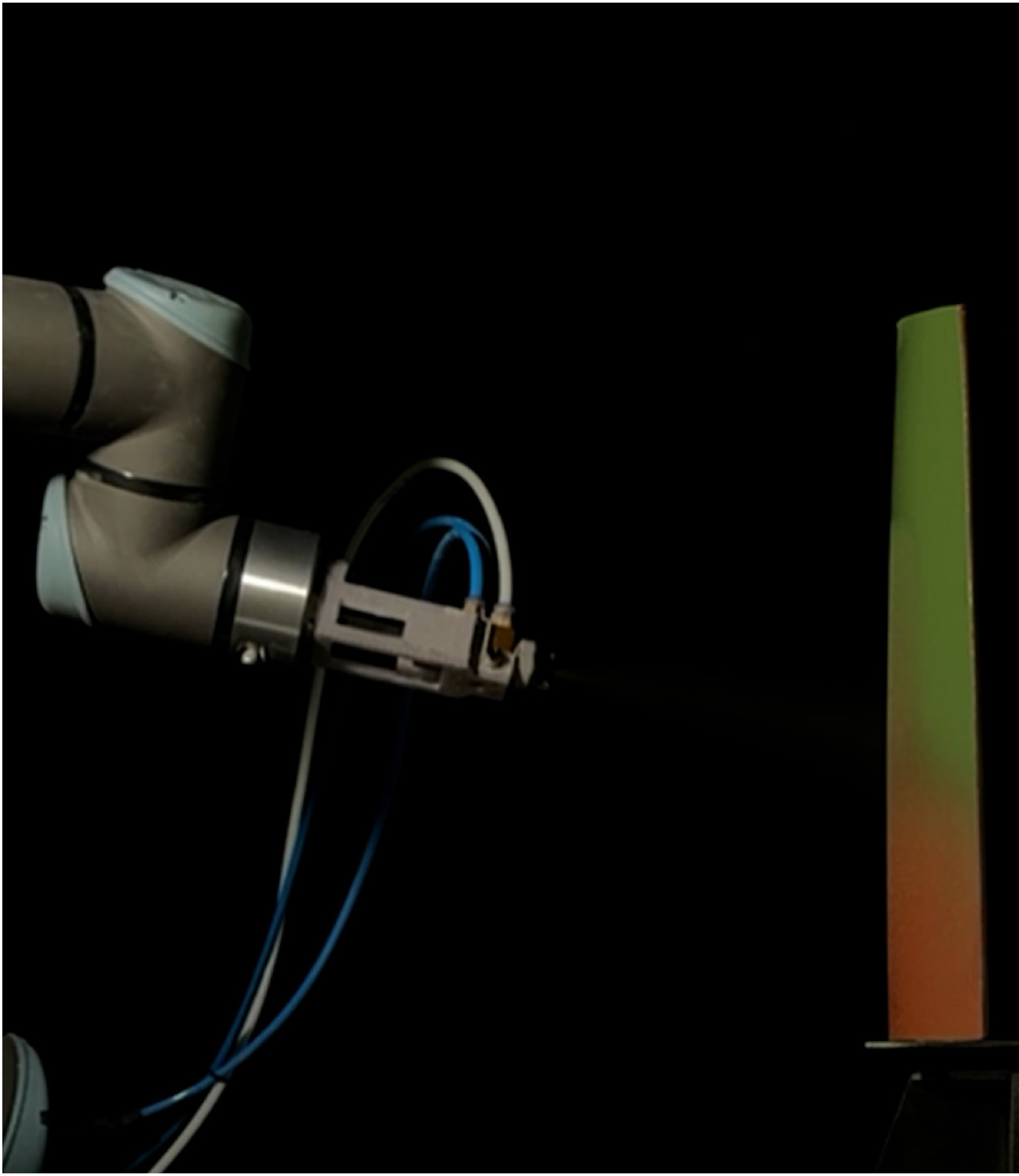


FIG 57 Human-Machine Collaboration - Robot Mimic 1

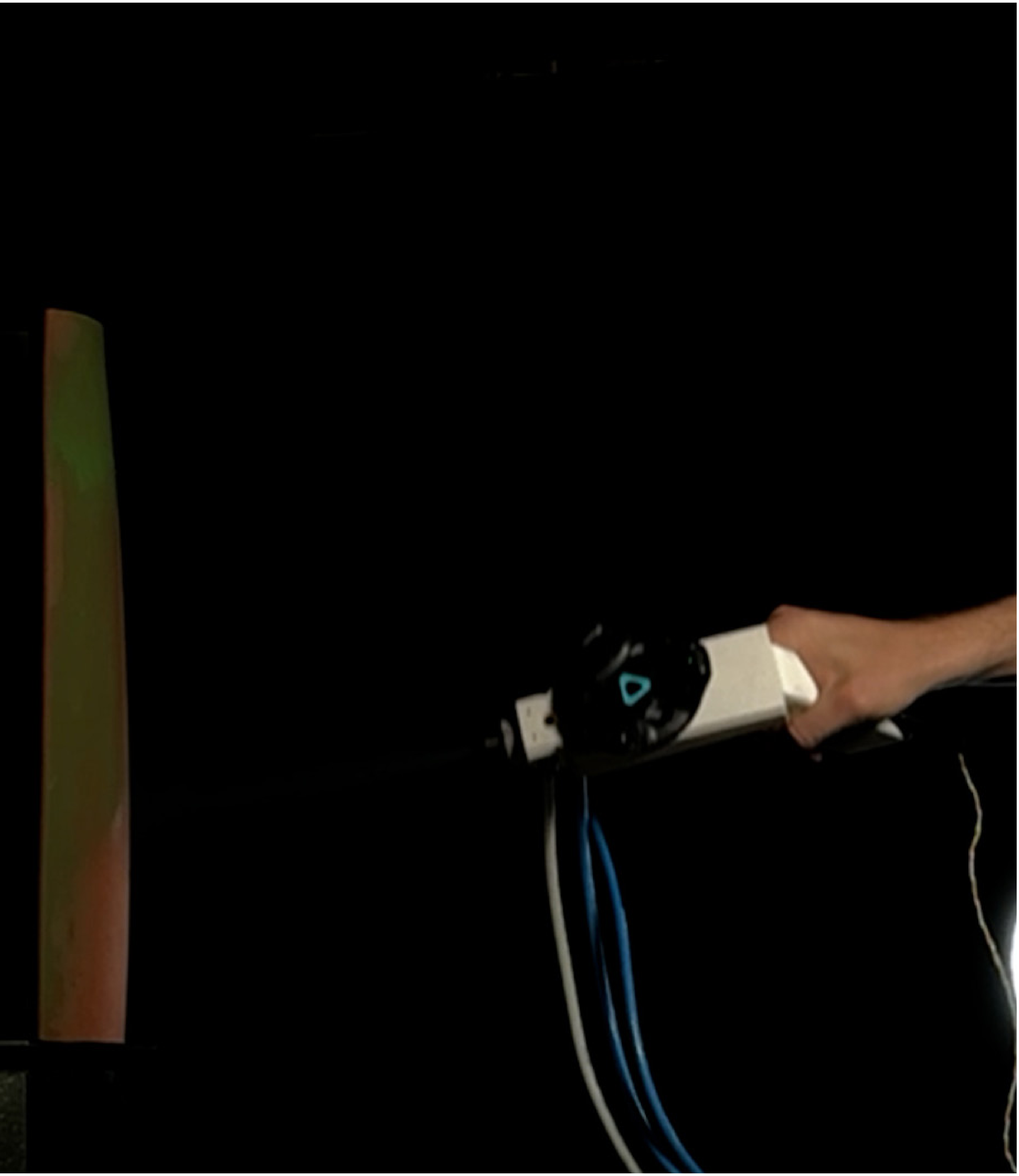
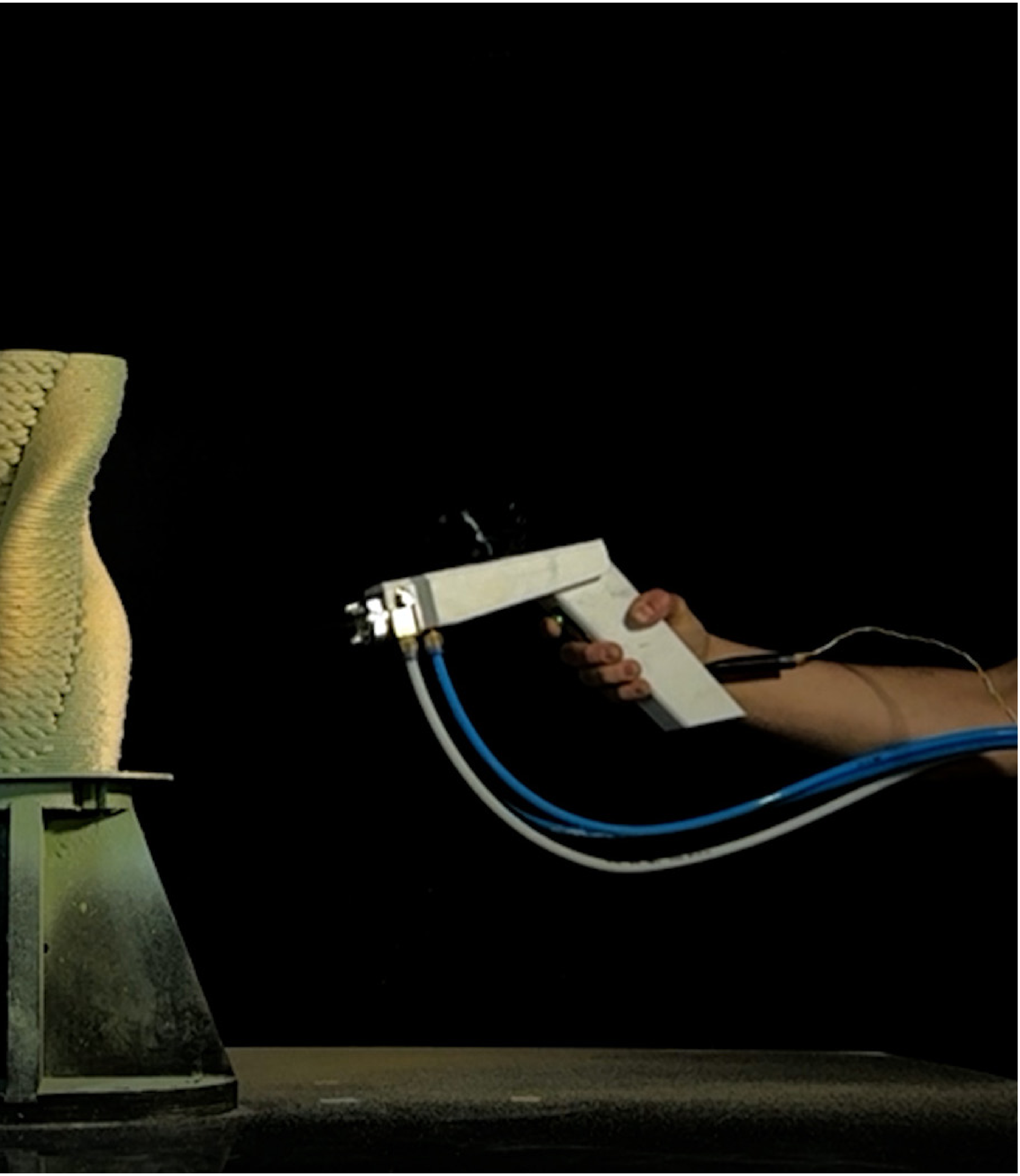


FIG 58 Human-Machine Collaboration - Robot Mimic 2



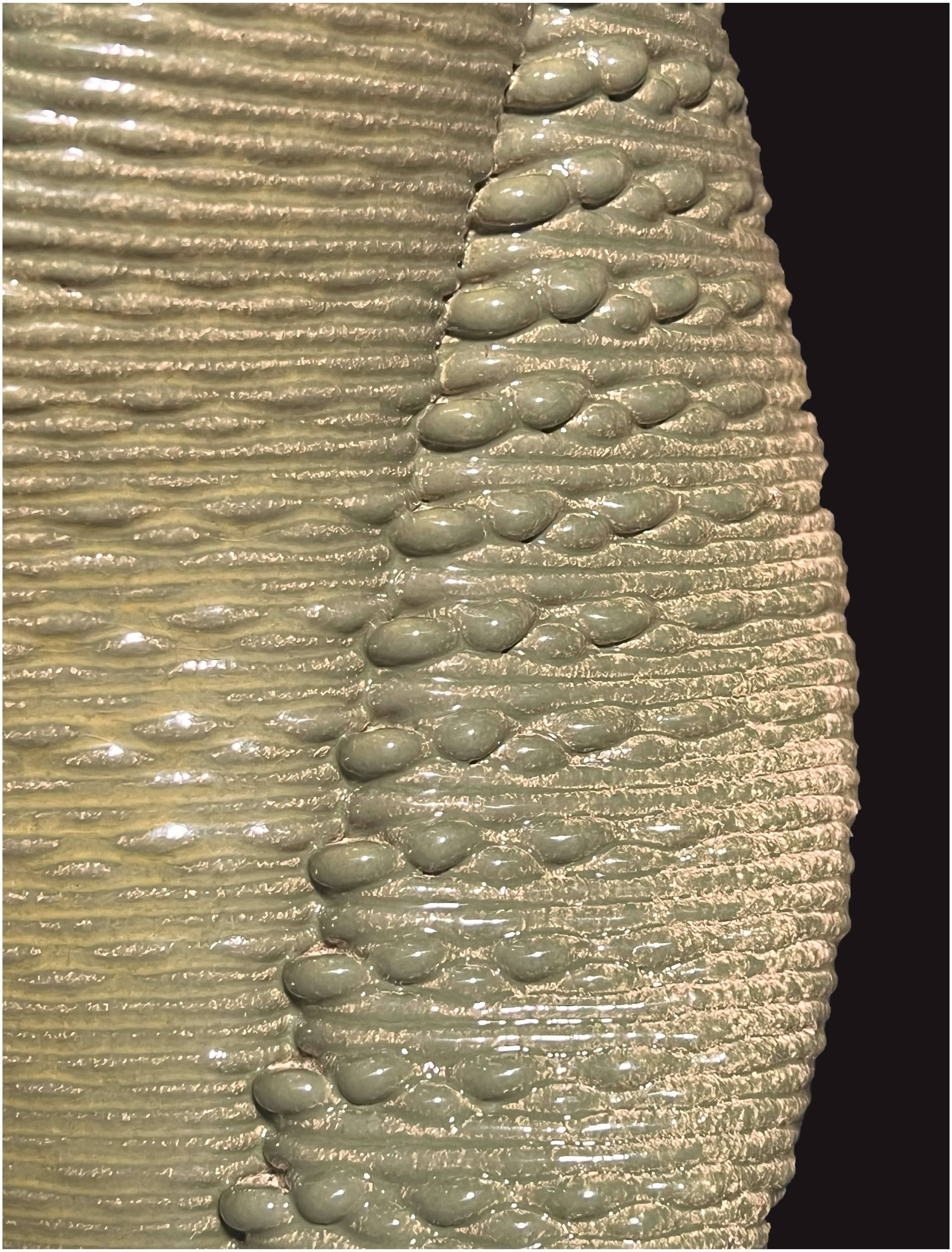


FIG 59 Glazing Green Vase Detail

FIG 60 Glazing Green Vase

FIG 61 Kema Ceramics Pablo Omar Pulido Spraying

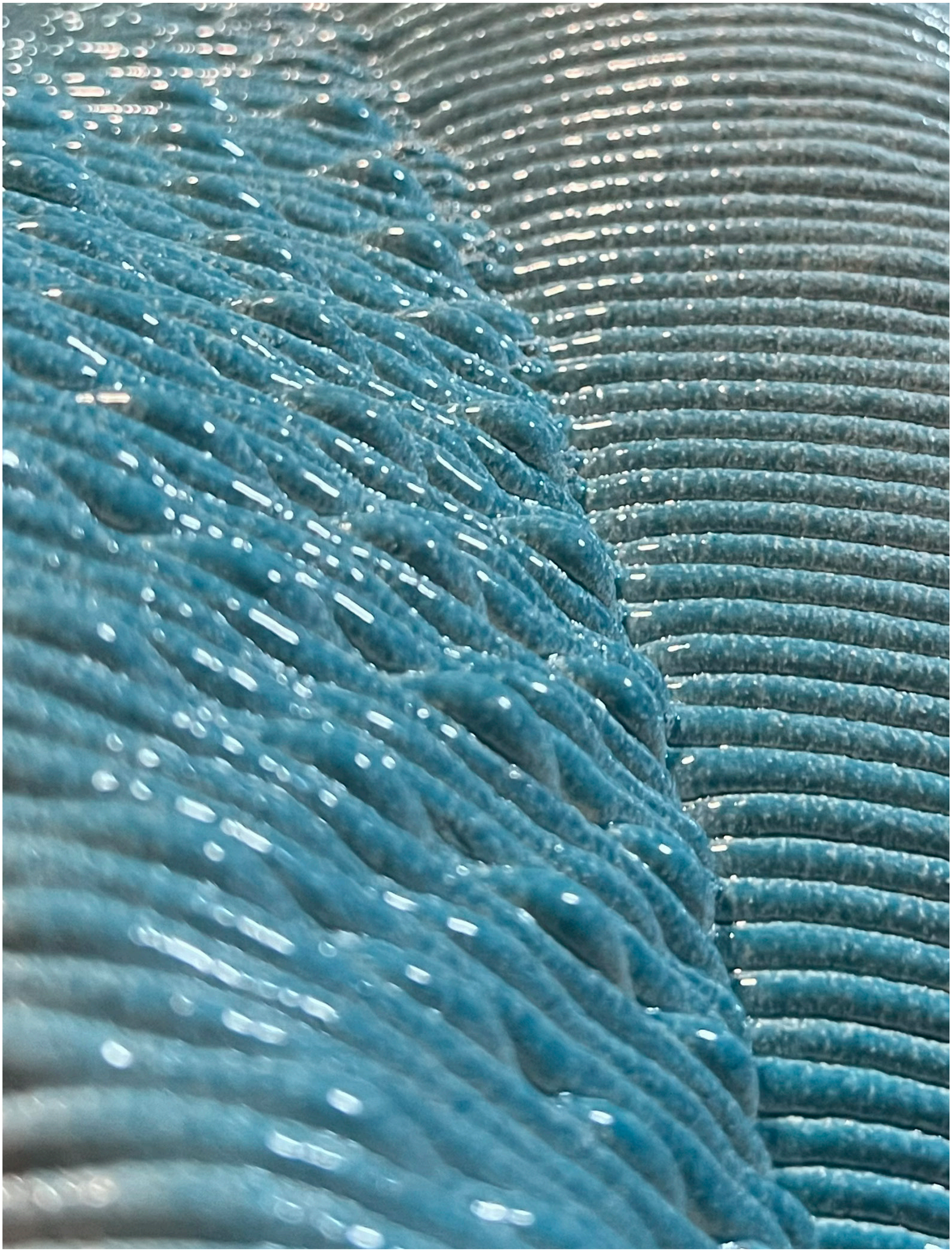


FIG 62 Kema Ceramics Spray Piece Detail

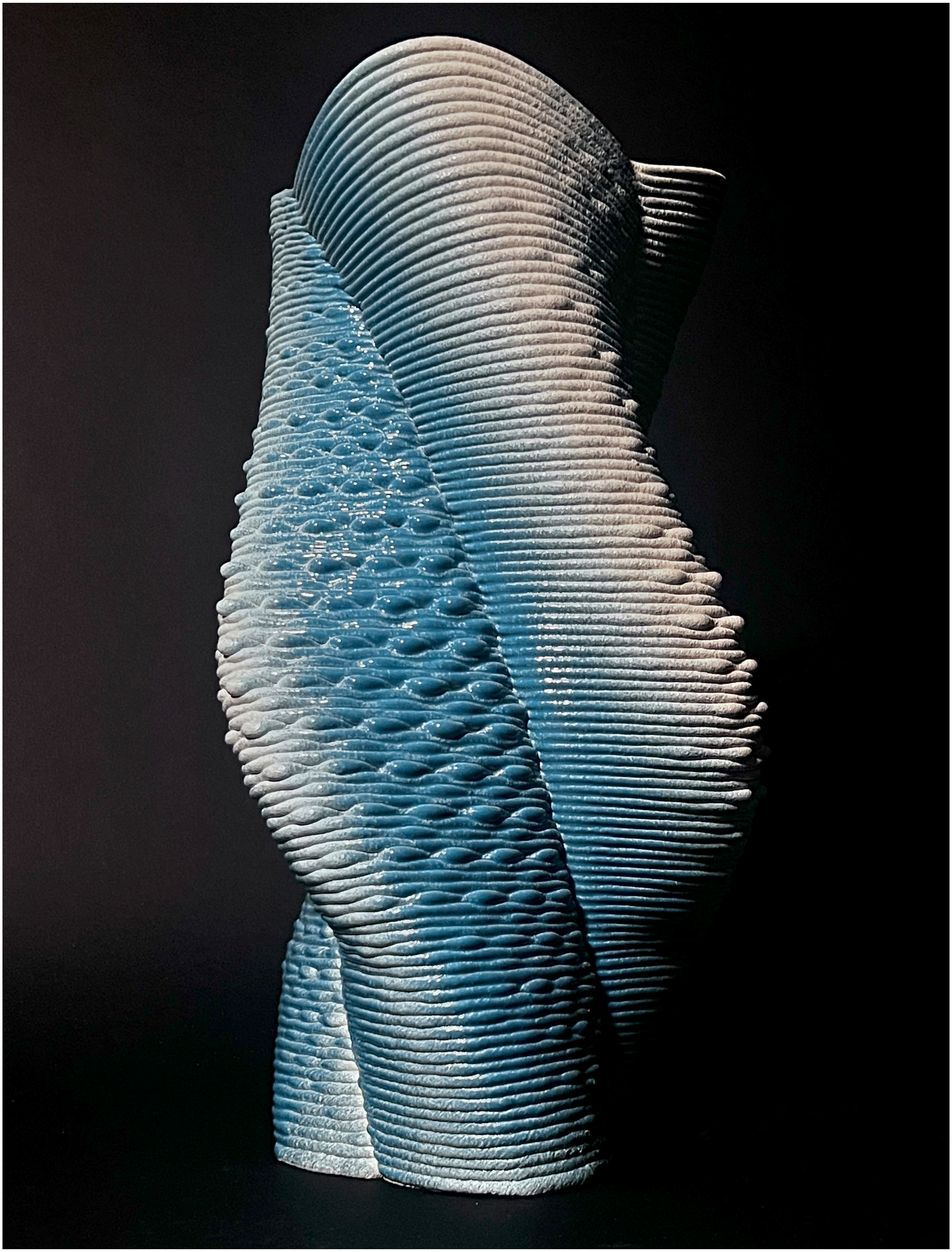


FIG 63 Kema Ceramics Full Body Shot

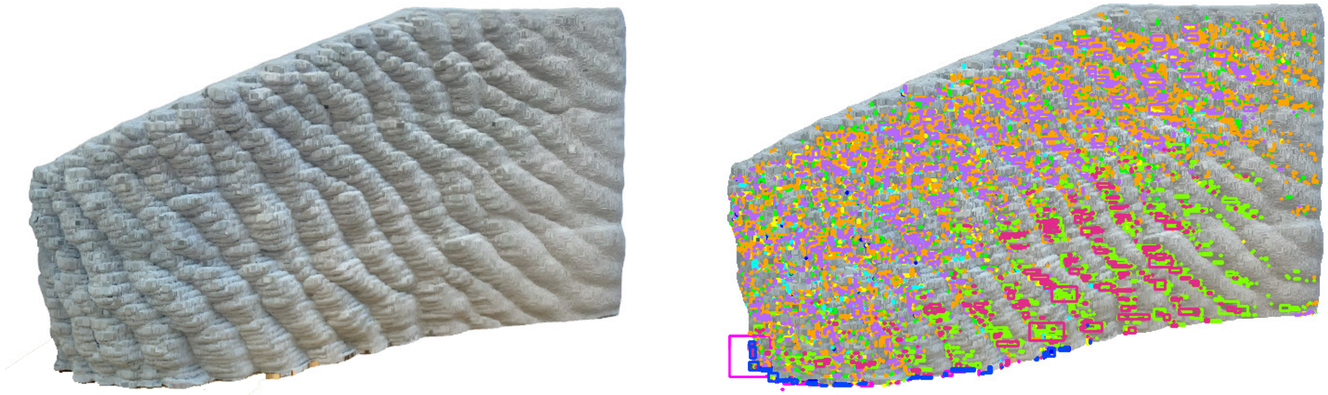


FIG 64 OpenCV Color Anomality Detection

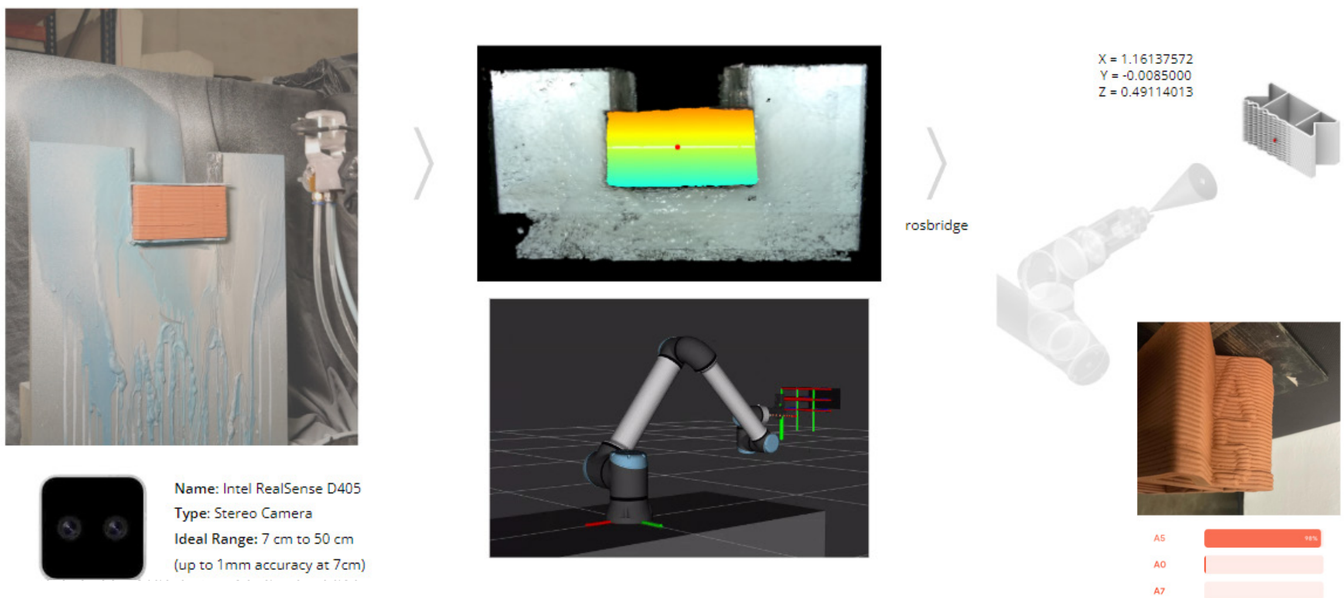


FIG 65 Identification-ROS-Reinforcement Learning

Machine Learning Adoption - Future Steps

In the realm of ceramics, the transition from pre-baked to post-baked pieces, especially in terms of glazing outcomes, can be both an art and a science. Predicting how a piece will look after it has been fired and glazed is a challenge that has long intrigued artists and scientists alike. Advances in computer vision and machine learning are now making it possible to forecast these results with remarkable accuracy, offering new possibilities in the ceramics industry.

The journey begins with capturing high-resolution images of the pre-baked pieces. Utilizing OpenCV, an open-source computer vision library, we can preprocess these images to enhance their quality. Techniques such as noise reduction, edge detection, and feature extraction are applied to highlight the intrinsic details of the piece's surface. These details include texture variations, color distributions, and any surface anomalies that might influence the final glazed appearance.

Machine learning, particularly convolutional neural networks (CNNs), plays a crucial role in this predictive process. These neural networks, built and trained using libraries such as TensorFlow or PyTorch, can learn complex patterns and relationships between the pre-baked features and the final glazed results. By feeding the model a substantial dataset of pre-baked images paired with their corresponding post-baked outcomes, the CNN can develop a predictive capability that simulates the glazing effects.

Clustering and segmentation techniques further refine this analysis. Methods such as K-means clustering and the Watershed algorithm, available in OpenCV, are used to divide the surface into distinct regions. These segmented areas are crucial for understanding how different parts of the piece will react to glazing and firing processes. For instance, regions with varying textures or color intensities might absorb glazes differently, resulting in diverse visual effects post-baking.

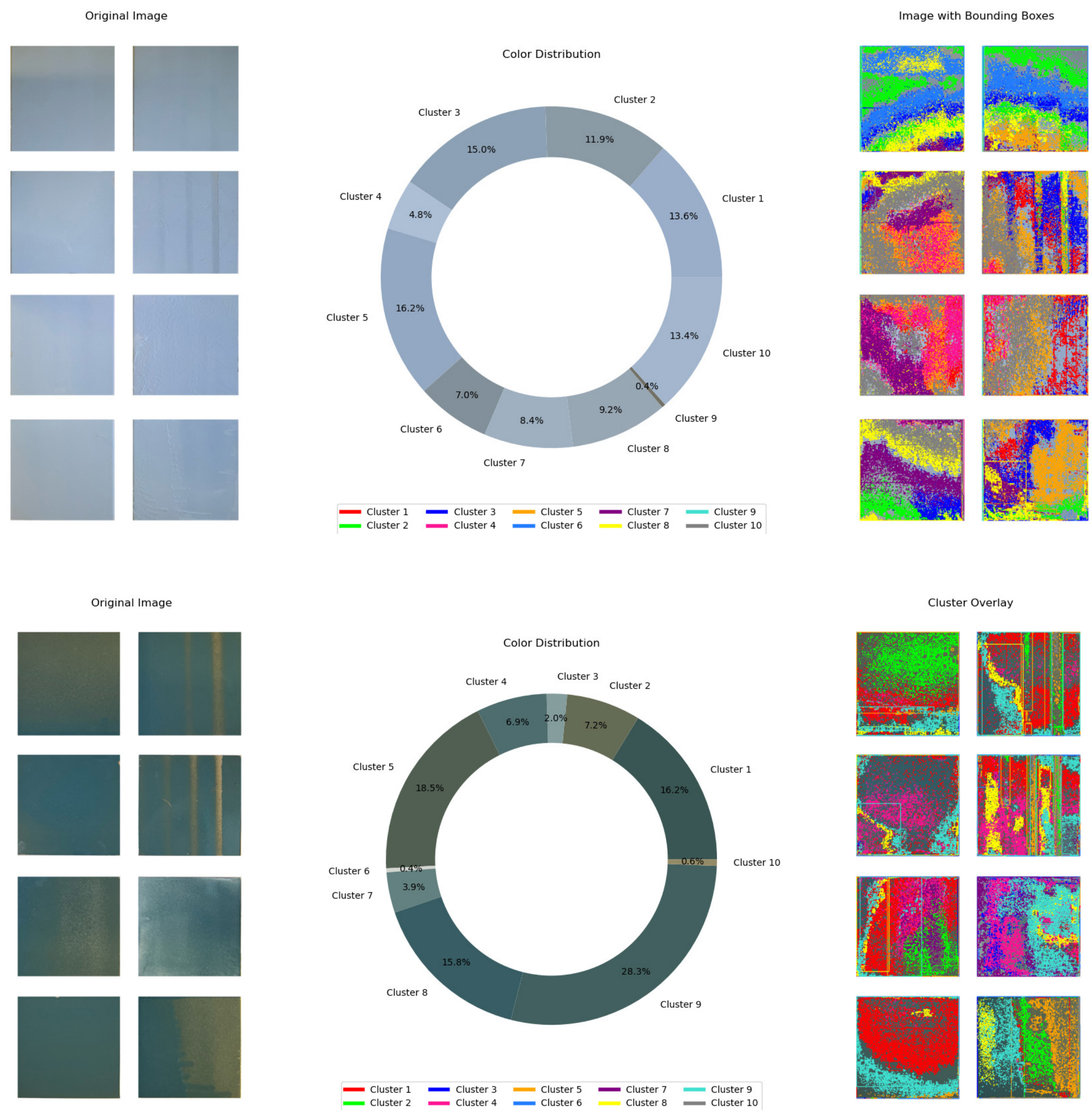


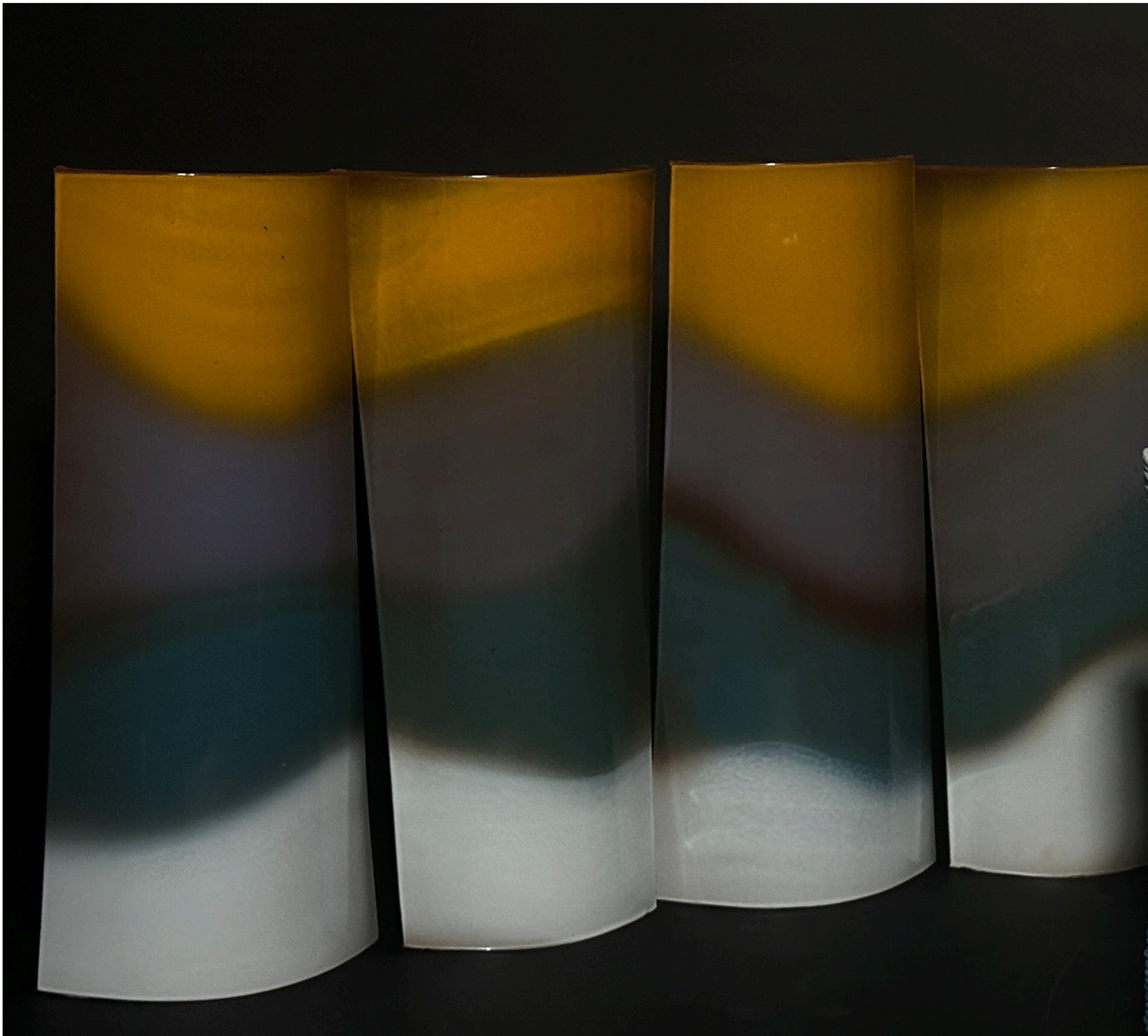
FIG 66 KClustering Color Segmentation

The images provided as reference illustrate the application of these techniques. The original pre-baked images are processed to identify and segment various clusters, which are then analyzed for their potential glazing outcomes. By combining these computer vision techniques with robust machine learning models, we can create a system that predicts the final appearance of a ceramic piece with high precision.

This integration of technology into the ceramics process not only enhances the efficiency of production but also allows for greater artistic control. Artists and designers can visualize the end result before the piece is even placed in the kiln, making informed adjustments to their methods. This predictive capability marks a significant advancement in the field, bridging the gap between traditional craftsmanship and modern technology, and ensuring that every piece that emerges from the kiln meets the desired aesthetic and quality standards.

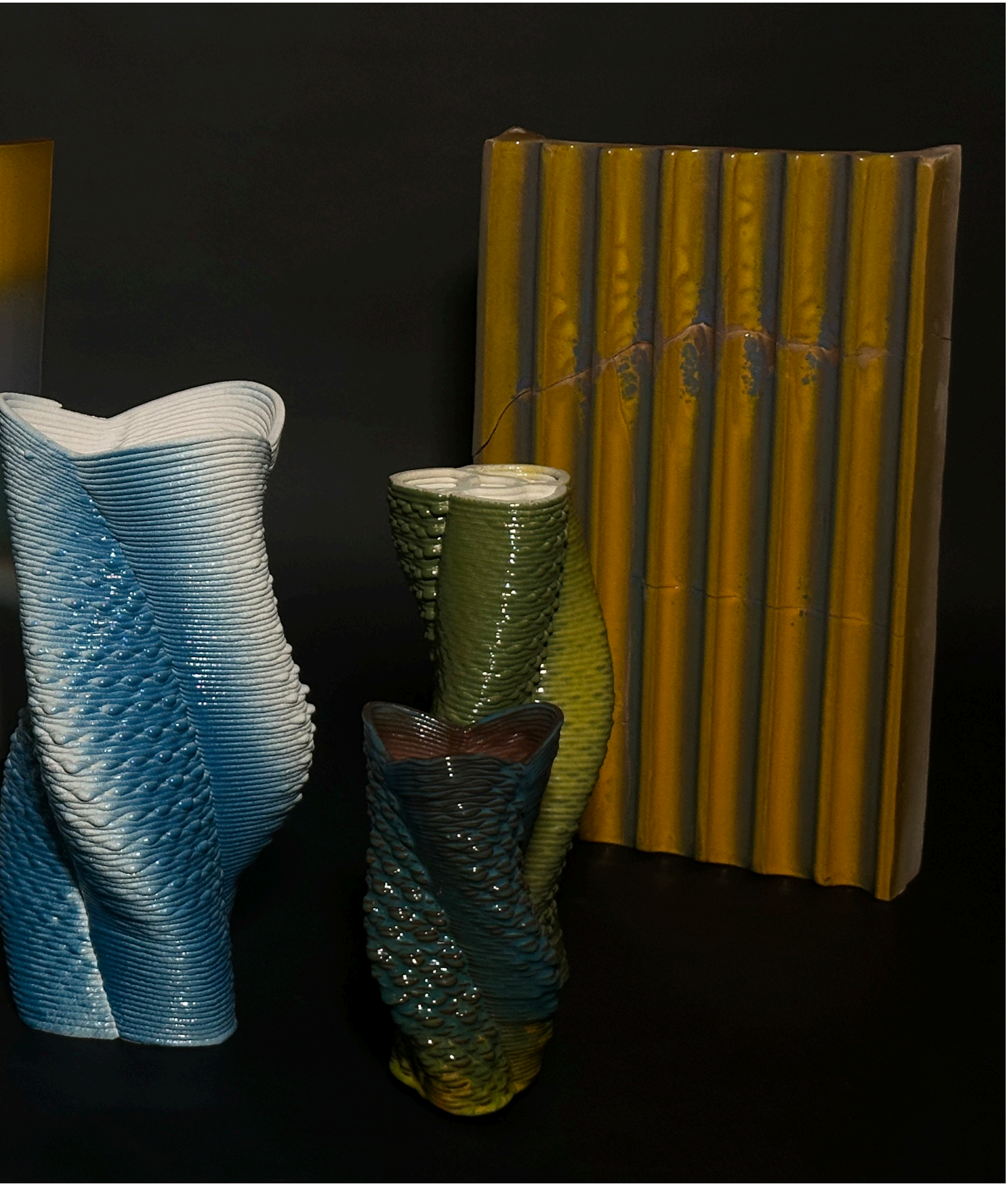
An important aspect that could be added to the data being embedded to every single piece could consist of the utilization of Computer vision and machine learning for piece identification. This could speed up the production process while allowing a type of intelligence to allow robots to become autonomous and become more efficient during time.

3D Print - Bake - Scan - Identify Piece/Load desired toolpath - 2nd Bake - Scan - Computer Vision (Collect Data) - Reinforcement Learning



Conclusions

Glazing Virtuoso represents a transformative project aimed at advancing the spray glazing industry by bridging the gap between human craftsmanship and robotic precision. Through the integration of advanced technologies and collaborative human-robot interaction, this initiative not only enhances artistic freedom but also establishes new standards in architectural and artistic fabrication. The projects showcased serve as a foundational step towards this future, underscoring our dedication to innovation and quality. We are pleased with the results achieved thus far and envision that with adequate resources and support, Glazing Virtuoso has the potential to revolutionize the creative landscape. It promises unparalleled capabilities and the fostering of limitless creativity in the realm of spray glazing and beyond, ushering in a new era of possibilities for artists and designers alike.



LETS COLOR THE WORLD