Converging Computer Vision and Deep Learning for Adaptive Printing on Irregular 3D Surfaces

M. Zenadocchio*, G. Battisti*, A. Marotta*, V. Di Nino†, G. De Vincentiis‡, A. Rabuffo‡
*University of L'Aquila, L'Aquila, Italy;
†Carvin Engineering SRL, Chieti, Italy;
‡Muchcolours SRL, Montesilvano, Italy;
Email: andrea.marotta@univaq.it

***Abstract*—This paper introduces an approach to enable AI-guided digital printing on 3D surfaces, overcoming the geometric limitations of conventional inkjet systems. Leveraging Mask R-CNN segmentation and real-time control logic, we demonstrate the feasibility of accurate, sustainable printing on complex geometries such as those found in fashion applications.**

***Index Terms*—AI, Vision, Printing, MASK R-CNN.**

I. Introduction

Digital inkjet printing has revolutionized the fashion and textile industries, offering unprecedented flexibility and print resolution on flat surfaces. However, a persistent limitation remains: current printheads require strict parallelism with the printing substrate, making it virtually impossible to decorate non-planar objects such as convex, concave, or irregular 3D surfaces [1].

To overcome this constraint, the project described in this work integrates a vision-guided printing system with artificial intelligence for object recognition and precise ink placement. Based on a Mask R-CNN architecture, the pipeline detects and segments any-shaped surface features (see Fig. 2) and applies textures only within the segmented regions. This significantly reduces alignment errors and material waste.

Unlike traditional systems, which rely on mechanical fixtures or pre-registered jigs, our system performs inference dynamically through a dedicated inference UI, adjusting confidence and mask filtering thresholds on the fly. As highlighted in [2], such AI-driven vision systems can greatly improve defect detection and surface targeting precision.

Moreover, the approach is suitable for conformal printing on geometries with curvature or partial occlusions [3]. By combining adaptive computer vision with specialized nano-pigment inks, the proposed method fosters sustainable printing practices, consistent with design trends in customization and material conservation [4].

II. System Overview

The proposed platform integrates an enhanced inkjet printer with a computer vision and control stack, enabling accurate printing on irregular 3D surfaces. The mechanical system includes a flatbed gantry equipped with a high-resolution camera rigidly mounted on the same axis as the printhead. This ensures spatial coherence between the acquired image and the surface to be printed.

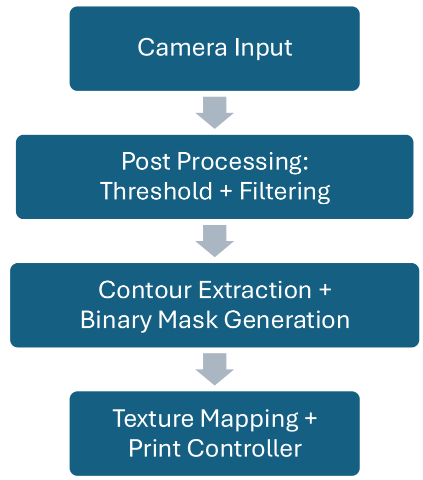


Fig. 1: System workflow: from visual acquisition to print execution.

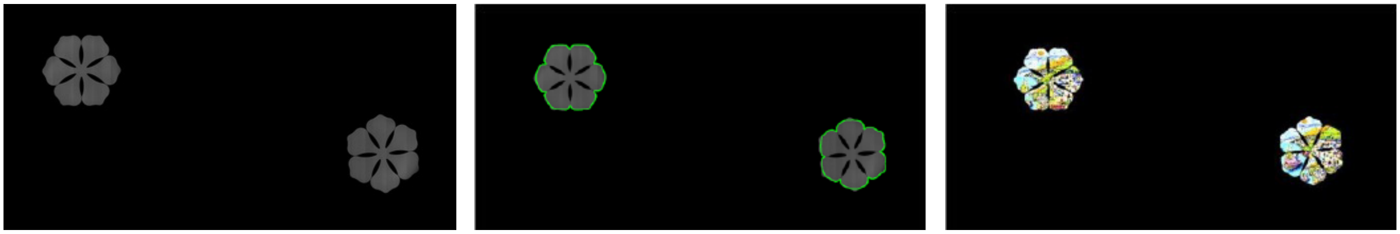
A dedicated embedded computing unit orchestrates the entire process. It handles image acquisition, invokes the deep learning inference engine, and relays spatial information to the printing controller. The printer supports variable-resolution inkjet heads and is compatible with nano-pigment inks tailored for adherence to non-planar substrates such as leather or treated polymer.

From a control perspective, the system does not rely on mechanical jigs or pre-calibrated templates. Instead, it operates dynamically, using vision-based inference to identify printable regions on-the-fly. This allows flexible adaptation to irregular geometries and heterogeneous object layouts.

A schematic overview of the data flow from image input to final actuation is presented in Fig. 1, while the AI-based segmentation logic is discussed in detail in the following section.

III. AI-Based Image Segmentation and Control Logic

The core of the recognition system is based on a Mask R-CNN model, pre-trained on the COCO dataset and repurposed for instance segmentation (floral shapes in the example)



(a) Input (b) Intermediate Output (c) Final Output

Fig. 2: Considered traffic patterns, achievable spatial lanes deactivation, and achievable energy savings.

commonly used in decorative fashion elements. Mask R-CNN combines a Region Proposal Network (RPN) with a fully convolutional network that performs pixel-wise object segmentation, enabling precise localization and delineation of printable features.

In our implementation, the model operates in inference mode and processes RGB images acquired directly from the overhead camera integrated into the printer's motion gantry. Once the image is captured, the Mask R-CNN pipeline outputs object masks, bounding boxes, class probabilities, and region scores. The masks represent high-confidence areas corresponding to target surface patterns, such as cavities or decorative impressions, onto which digital texture can be applied.

To facilitate real-time adaptation to different printing scenarios, we developed an interactive control interface based on OpenCV. This user interface exposes adjustable parameters such as:

- **Detection Confidence Threshold:** filters out uncertain detections below a configurable confidence value (typically 0.6).
- **Non-Maximum Suppression (NMS) Threshold:** resolves overlapping masks by suppressing redundant proposals based on their Intersection-over-Union (IoU).
- **Minimum Area Filter:** discards small or spurious segments to ensure that only physically meaningful print zones are retained.

Contours are extracted from each filtered mask using the Suzuki–Abe algorithm. These contours are further post-processed to eliminate regions that either overlap the image border, fall outside the expected size range, or deviate from the predefined geometric regularity.

The resulting contours define printable areas and are used to generate a high-resolution binary mask image, which is forwarded to the printing controller. This controller aligns the selected texture with the contour mask and synchronizes the actuation of the inkjet head accordingly.

This real-time interaction between deep learning segmentation and physical actuation enables on-the-fly print region definition without mechanical jigs or prior calibration. In particular, it is robust to moderate rotations, partial occlusions, and irregular spacing among the decorative elements, as demonstrated in our experiments.

A schematic view of this control logic is provided in Fig. 1, outlining the sequential pipeline from image acquisition to texture deposition.

IV. Experimental Validation

A sample image processin of uniformly spaced flower-like objects processed through the detection pipeline is shown in Fig. 2. It can be noticed that the pipeline successfully extracted the relevant regions and applied a texture within the segmented holes. The texture was aligned precisely within object boundaries, without requiring external calibration or mechanical jigs.

The results validate the feasibility of automated 3D-aware segmentation and image transfer. Further tests will involve the application of the pipeline to real, concave/convex decorated substrates such as leather, metal, and polymer samples.

V. Conclusion and Future Work

This work introduces a hybrid AI-vision solution for non-planar inkjet printing, specifically tailored for fashion and accessory applications. By integrating Mask R-CNN segmentation with a controllable printing interface, the system achieves localized, high-precision texture application.

Future developments will include enhancing robustness under varying illumination and integrating feedback from real print results to fine-tune the recognition pipeline.

Acknowledgment

This work is partially supported by Abruzzo Region through POR FESR Abruzzo 2021/2027 Programme – Measure 1.1.1.1 (CUP C79J24000100007) and by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, National Innovation Ecosystem (ECS00000041 - VITALITY - CUP E13C22001060006).

References

[1] J. Ren, G. Chen, and X. Li, "A fine grained digital textile printing system based on image registration," *Computers in Industry*, vol. 92, pp. 152–160, 2017.

[2] Z. Li and M. Chen, "An efficient printing defect detection based on yolov5-dcn-lsk," *Sensors*, vol. 24, no. 23, p. 7429, 2024.

[3] C. Rodriguez-Padilla, E. Cuan-Urquizo *et al.*, "Algorithm for the conformal 3d printing on non-planar tessellated surfaces: Applicability in patterns and lattices," *Applied Sciences*, vol. 11, no. 16, p. 7509, 2021.

[4] A. Teron, "Digital printing: The new era in fashion and textile design," in *Emerging Trends in Traditional and Technical Textiles (ICETT 2023)*, ser. Springer Proceedings in Materials, vol. 55. Springer, 2025, pp. 195–201.