Toward Inkjet Additive Manufacturing Directly onto Human Anatomy

Reed A. Johnson[1]
John J. O'Neill[1]
Rodney L. Dockter[1]
Timothy M. Kowalewski[1]**, PhD**

Department of Mechanical Engineering
University of Minnesota[1]

1 Background

Bioprinting technology has been rapidly increasing in popularity in the field of tissue engineering. Potential applications include tissue or organ regeneration, creation of biometric multilayered skin tissue, and burn wound treatment [1].

Recent work has shown that living cells can be successfully applied using inkjet heads without damaging the cells [2]. Electrostatically driven inkjet systems have the benefit of not generating significant heat and therefore do not damage the cell structure. Inkjets have the additional benefit of depositing small droplets with micrometer resolution and therefore can be used to build up tissue like structures.

Previous attempts at tracking and drawing on a hand include either direct contact with the hand [3] or tracking the hand only in two degrees of freedom [4]. In this work we present an approach to track a hand with three degrees of freedom and accurately apply a substance contact free to the hand in a desired pattern using a bioprinting compatible inkjet. The third degree of freedom, in this case depth from the hand surface, provides improved control over the distance between the inkjet head and object, thus increasing deposition accuracy.

2 Methods

The end effector of a UR5 robotic arm (Universal Robots, Odense, Denmark) was fitted with both a tool, a Hewlett Packard (Palo Alto, CA) inkjet print cartridge, and a 3-D scanning hand tracker, in this case a Leap Motion controller (Leap Motion Inc. San Francisco, CA). A fixture was designed and constructed to mount the inkjet and Leap Motion in the desired positions, as shown in Figure 1 (A). This configuration allows space between the inkjet and the sensor for a hand to be positioned to be printed on. The inkjet head was controlled via an Arduino microcontroller and a custom circuit to control the deposition of ink from each inkjet independently.

The software to implement this approach was written using the Robotic Operating System (ROS) and supporting libraries. The control algorithm consisted of two fundamental components. First a black and white image was loaded which served as the template for the ink pattern. This template was analyzed and the locations of all pixels requiring ink were stored as target locations $P_{target} = [X,Y]$. The second component of this algorithm was online ink deposition. In this step the information from the Leap sensor was used to determine the location of the hand relative to the inkjet head. An initial calibration step is also performed wherein the hand is touched to the inkjet head. That location is recorded as the origin of the inkjet relative to the hand (P_{inkjet}). Using the next known target ink location, an overall position error was computed using visual servoing error.

This error was then used along with the forward kinematic jacobian for the UR5 in order to compute an instantaneous end effector velocity in three dimensions. The resultant trajectories are continuously recalculated until the inkjet is positioned over the target location on the hand, then ink is deposited. Additionally, while the inkjet is traveling to the current target location, all locations that it passes over are queried in the list of remaining target locations. Ink is deposited any time the inkjet is positioned over any location requiring ink.

The primary experiment in this work was to print the University of Minnesota's block 'M' on a stationary hand. A block 'M' image was imported and the appropriate trajectory was calculated by the algorithm. The hand in this scenario is a molded mannequin hand with white copy paper attached to the back to absorb the ink from the inkjet, as seen in Figure 1 (B). The Leap Motion sensor on the robot measured the $P_{hand} = [X,Y,Z]$ location of the mannequin hand and calculated the appropriate trajectory for the inkjet to print the picture. This process allows the hand to be unconstrained while being printed onto.

To evaluate the accuracy of this printing approach, the resultant print of the block 'M' on the copy paper was scanned for digital analysis. The scanned image was then imported into MATLAB (Mathworks Inc, Natick, MA) to quantify the performance characteristics. Since the image was located relative to the inkjet origin, the location was not considered relevant to analy-

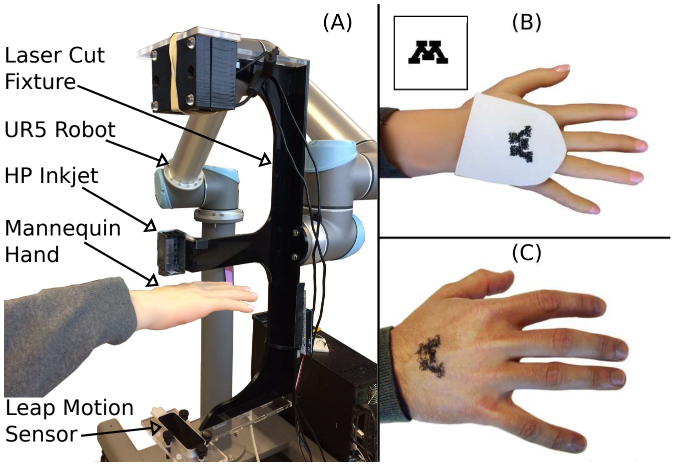

FIGURE 1: (A) Experiment setup. (B) Results overview. (C) Proof of concept: Human print.

sis, therefore the scanned image was first manually scaled and translated so that the image size and location matched that of the template image. Then an exhaustive search of X, Y and Theta was performed to finalize registration to the template.

It has been shown that the Leap Motion sensor has a noise value of 0.7 mm [5]. This value is used as a noise balloon inflated around the target area while interpreting the performance results. Error was calculated at each pixel in the template image as the deviation in grayscale value between the template image and the corresponding pixel in the scanned image. The average error between template and scan across the whole image was used as a performance metric.

3 Results

Three primary metrics were analyzed, these include the number of pixels covered with ink in the desired area, the number of pixels with ink in the balloon area (acceptable due to measurement noise), and the number of pixels with ink outside both the desired and balloon areas (true error). A summary of the results can be seen in Table 1.

A visual representation of the data is shown in Figure 2. The printed image is largely similar to the desired image having achieved a coverage of 31,366 of the desired 36,630 pixels (85.6 %) and only allowing 1.2 % of the total ink outside the balloon.

Additionally, the overall process of inking took a total of 340 seconds. This was for the block 'M' trajectory which consisted of 1044 total pixels. This results in a average time of 0.33 seconds per pixel, for a single layer.

4 Interpretation

The experimental results indicate that a robotic arm can successfully be used to control an inkjet head to project a liquid on human anatomy in a controlled manner. This approach is contact free to within the tolerances of the sensor and requires no constraints on the position or rigidity of the anatomy. This analysis was limited to a stationary mannequin hand. However, as a proof of concept for free moving human anatomy we ran the same algorithm on an unsupported hand of the author which can be seen in Figure 1 (C).

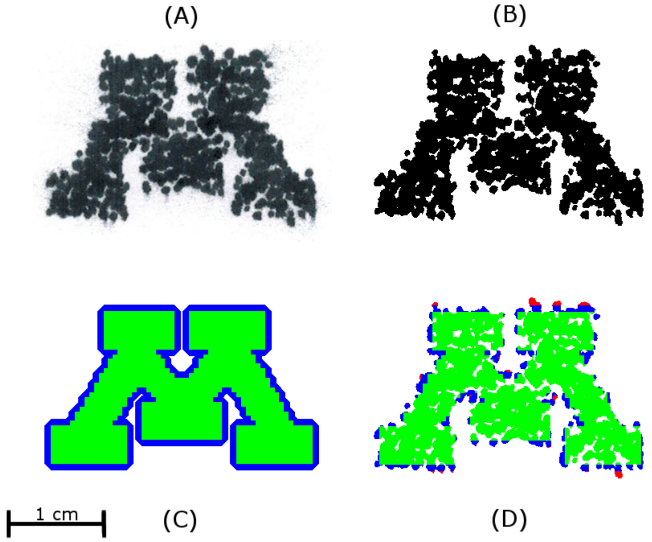

FIGURE 2: (A) Printed Scanned M. (B) Printed Threshold M. (C) Desired M (green) with 0.7 mm balloon (blue). (D) Printed M metrics (error in red).

Future work will consist of testing different densities of ink and comparing them to determine if it is possible to achieve a better accuracy while reducing the amount of ink outside the desired area. Additional experiments will be performed to evaluate the tracking and inking accuracy for moving anatomy. In general this setup and approach is well suited for printing on human anatomy and is a first step towards bioprinting directly onto unconstrained human anatomy using cells.

TABLE 1: Ink Distribution

Location of Ink	Pixel Count	Total Ink
Ink in Target Area	31,366	86.1%
Ink Inside Balloon (acceptable error)	4623	12.7%
Incorrect Ink (true error)	422	1.2%

REFERENCES

[1] Seol, Y.-J., Kang, H.-W., Lee, S. J., Atala, A., and Yoo, J. J., 2014. "Bioprinting technology and its applications". European Journal of Cardio-Thoracic Surgery, p. 148.

[2] Nakamura, M., Kobayashi, A., Takagi, F., Watanabe, A., Hiruma, Y., Ohuchi, K., Iwasaki, Y., Horie, M., Morita, I., and Takatani, S., 2005. "Biocompatible inkjet printing technique for designed seeding of individual living cells". Tissue engineering, **11**(11-12), pp. 1658–1666.

[3] O'Neill, J. J., and Kowalewski, T. M., 2014. "Online free anatomy registration via noncontact skeletal tracking for collaborative human/robot interaction in surgical robotics". Journal of Medical Devices, **8**(3), p. 030952.

[4] French, A., O'Neill, J., and Kowalewski, T. M., 2016. "Design of a dynamic additive manufacturing system for use on free-moving human anatomy". Journal of Medical Devices, **10**(2), p. 020941.

[5] Weichert, F., Bachmann, D., Rudak, B., and Fisseler, D., 2013. "Analysis of the accuracy and robustness of the leap motion controller". Sensors, **13**, pp. 6380–6393.