

Closed-loop Tool Path Planning for Non-planar Additive Manufacturing and Sensor-based Inspection on Stationary and Moving Freeform Objects

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ABSTRACT

Additive manufacturing (AM) has received much attention from researchers over the past decades because of its diverse applications in various industries. AM is an advanced manufacturing process that facilitates the fabrication of complex geometries represented by computer-aided design (CAD) models. Traditionally, designed parts are fabricated by extruding material layer-by-layer using a tool path planning obtained from slicing programs by using CAD models as an input. Recently, there has been a growing interest in non-planar AM technologies, which offer the ability to fabricate multilayer constructs conforming to freeform surfaces. Non-planar AM processes have been utilized in various applications and involved objects of varying material properties and geometric characteristics. Although the current state of the art suggests AM can provide novel opportunities in conformal manufacturing, several challenges remain to be addressed. The identified challenges in non-planar AM fall into three categories: 1) conformal 3D printing on substrates with complex topography of which CAD model representation is not readily available, 2) understanding the relationship between the tool path planning and the quality of the 3D-printed construct, and 3) conformal 3D printing in the presence of mechanical disturbances. An open-loop non-planar tool path planning algorithm based on point cloud representations of object geometry and a closed-loop non-planar tool path planning algorithm based on position sensing were

proposed to address these limitations and enable conformal 3D printing and spatiotemporal 3D sensing on objects of near-arbitrary organic shape. Three complementary studies have been completed towards the goal of improving the conformal tool path planning capabilities in various applications including fabrication of conformal electronics, *in situ* bioprinting, and spatiotemporal biosensing:

- i. A non-planar tool path planning algorithm for conformal microextrusion 3D printing based on point cloud data representations of object geometry was presented. Also, new insights into the origin of common conformal 3D printing defects, including tool-surface contact, were provided. The impact and utility of the proposed conformal microextrusion 3D printing process was demonstrated by the fabrication of 3D spiral and Hilbert-curve loop antennas on various non-planar substrates, including wrinkled and folded Kapton films and origami.
- ii. A new method for closed-loop controlled 3D printing on moving substrates, objects, and unconstrained human anatomy via real-time object position sensing was proposed. Monitoring of the tool position via real-time sensing of nozzle-surface offset using 1D laser displacement sensors enabled conformal 3D printing on moving substrates and objects. The proposed control strategy was demonstrated by microextrusion 3D printing on oscillating substrates and *in situ* bioprinting on an unconstrained human hand.
- iii. A reverse engineering-driven collision-free path planning program for automated inspection of macroscale biological specimens, such as tissue-based products and organs, was proposed. The path planning program for impedance-based spatiotemporal biosensing was demonstrated by the characterization of meat and fruit tissues using two impedimetric sensors: a cantilever sensor and a multifunctional fiber sensor.

Closed-loop Tool Path Planning for Non-planar Additive Manufacturing and Sensor-based Inspection on Stationary and Moving Freeform Objects

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GENERAL AUDIENCE ABSTRACT

Additive Manufacturing (AM), commonly referred to as 3D printing, is a computer-aided manufacturing process that facilitates the fabrication of personalized and customized models, tissues, devices, and wearables. AM has several advantages over traditional manufacturing processes. For example, directing computer-driven robotics enables control over spatial structure and composition of parts. While 3D printing is typically performed using layer-by-layer planar tool paths generated by slicing programs, non-planar 3D printing is an emerging area that has recently been examined for various post-processing applications. Processes that enable material deposition conforming to complex geometric and freeform objects (*e.g.*, anatomical structures), are central to various industries, including additive manufacturing, electronics manufacturing, and biomanufacturing. In this dissertation, tool path planning methods and real-time control strategies for non-planar 3D printing onto stationary and moving arbitrary surfaces, and various conformal electronics and *in situ* bioprinting applications will be presented. In addition to the tool path planning methods for 3D printing, a collision-free path planning program will be proposed for the inspection of large tissues and organs. The utility of the proposed method will be demonstrated through electrical impedance-based biosensing of meat and fruit to characterize their compositional and physiochemical properties which are used for quality assessment.

DEDICATION

For my late father, Abdullah Kucukdeger, who always believed in me.

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1 Introduction

1.1 Background and Motivation

Additive manufacturing, commonly referred to as 3D printing, is an emerging multi-material computer-aided manufacturing process. Through the use of planar tool paths, 3D printing enables spatial control over the microstructure and composition, and thus, mechanical properties of a resultant material or part [1,2]. It also reduces the need for pre-processing operations, such as creating complex masks and dies. Among all 3D printing processes, which include stereolithography, inkjet printing, and microextrusion printing, microextrusion 3D printing processes have received considerable attention due to their compatibility with a wide range of materials, including cell-laden biomaterials and polymer composites (*e.g.*, containing functional nanomaterials) [1–6]. In microextrusion 3D printing, bioink is dispensed through a nozzle layer-by-layer following a tool path plan under the control of a fluid-dispensing system and a robotic system. Hence, this system enables users to automatically obtain planar path plans using commercial slicing software by using a computer-aided-design (CAD) model as an input [3]. In microextrusion 3D printing, the nozzle standoff distance is one of the important process parameters to control since it affects the ink flow properties and the geometric accuracy of the printed filament [7–10]. The standoff distance refers to the distance between the nozzle tip and the depositing surface. Hence, the objective is to maintain a nozzle standoff distance (*i.e.*, extruder-object separation) throughout the process that enables high quality deposition of the 3D printed material on the surface. High standoff distance may result in discontinuous filament due or poor adhesion to the substrate or filament disposition, while low standoff distance may contribute to spreading or buildup material [7–10]. While 3D printed parts are typically fabricated using layered, planar

tool paths generated from slicing programs, non-planar tool path planning has recently been examined for post-processing modification of such parts, including reinforcement, finishing, and repair operations [11–13]. In planar 3D printing, the nozzle standoff distance is constant since the surface normal direction does not change across the planar build plate, whereas the ideal standoff distance needs to be adaptively adjusted depending on the surface properties in non-planar 3D printing. However, the relationship between the surface properties and the optimal standoff distance for non-planar 3D printing, also referred to as conformal 3D printing, has not yet been established. State-of-the-art conformal 3D printing strategies require: 1) objects of known geometry that can be described by either analytical expressions or CAD models, 2) planar 3D printing on flexible substrates which are subsequently shaped to a curved surfaces through a forming process, or 3) tool path length scales that are significantly smaller than the object's radius of curvature. Hence, non-planar path planning methodologies, that enable quality conformal 3D printing on objects with freeform surfaces of which CAD models are not readily available, may considerably expand opportunities for repairing and augmenting objects of complex geometry.

The growing interest in additive manufacturing has increased the need for quality control processes to ensure the accuracy of the printed constructs. Several researchers addressed the problem of quality analysis by generating quality prediction and assessment methods that are performed post process in various additive manufacturing techniques such as material jetting, binder jetting and directed energy deposition processes [14–16]. However, currently proposed processes are based on open-loop control with limited sensing capabilities. Incorporating sensing tools to the printing platform and closed-loop feedback control would allow real-time process control to enhance the product quality. While considerable studies have been conducted on real-

time process control techniques for additive manufacturing, there remains a demand for methods that enable fabrication of constructs conforming to the freeform surface of moving substrates and objects. The ability to 3D print materials onto moving substrates has the potential to enable novel *in situ* bioprinting and 3D printing systems to be used in surgical and extreme settings, such as space stations and moving vehicles, that are prone to mechanical disturbance and motion.

Tool path planning methodologies have been used not only for 3D printing processes but also for inspection processes. Automated inspection planning has been widely studied over the past decades. However, previous research has mostly focused on computer-aided inspection planning for coordinate measuring machines (CMM) which are used for dimensional inspection of manufactured parts [17–21]. Path planning methods for automated inspection processes can be extended to the inspection of macroscale biological tissues. Automated inspection methods provide economical, convenient, and accurate quantitative analysis of samples and products in various industries including agriculture, pharmaceutical, and biotechnology. Thus, new methods for inspection path planning that enable the spatiotemporal characterization of macroscale tissues and organs with freeform surfaces could improve inspection processes in various applications involving large biological constructs, such as assessment of food products, bioprinted tissues, and donor organs.

1.2 Research Objectives

The overall objective of this dissertation was to develop new processes and methods for conformal additive manufacturing on both stationary and moving freeform surfaces with path lengths that are significantly larger than the object's radius of curvature ($L_p \gg R$), and for

impedance-based spatiotemporal inspection of biological constructs. Specifically, this work aims to develop and validate:

- I. A reverse engineering-based path planning method to achieve quality conformal 3D printing on objects with freeform surfaces that exhibit arbitrary topographical features using a 3-axis system.
- II. A feedback control system to enable conformal 3D printing on freeform surfaces in settings prone to mechanical disturbance and substrate movement during manufacturing using a laser displacement sensor.
- III. A collision-free inspection planning program for spatiotemporal 3D impedance mapping of macroscale tissues and organs using impedimetric sensors.

1.3 Dissertation Organization

This dissertation is organized as follows. The state-of-the-art in non-planar tool path planning is reviewed in Chapter 2. In Chapter 3, the point cloud-based path planning (PCPP) methodology is proposed for conformal 3D printing on freeform surfaces. Chapter 4 presents a closed-loop control strategy for conformal 3D printing on moving substrates. A collision-free path planning methodology for spatiotemporal biosensing of tissues is presented in Chapter 5. Finally, Chapter 6 summarizes the contribution of this dissertation and discusses future research directions.

2 Literature review

In this section, a review of the current state-of-the-art in non-planar tool path planning is introduced. Specifically, existing non-planar toolpath programming methodologies is described in Section 2.1. Subsequently, Section 2.2 discusses the non-planar additive manufacturing processes and recent progress in conformal additive manufacturing. Bioprinting and path planning strategies for *in situ* bioprinting are examined in Section 2.3. Finally, path planning for inspection processes are described in 2.4.

2.1 Non-planar Tool Path Planning

The study of algorithms to control tool movement through non-planar paths or across objects with curved surfaces, often referred to as non-planar tool path planning, has emerged as an important aspect of computer-aided manufacturing for contact and non-contact manufacturing processes and post-processing operations [22–28]. Iso-parametric, -planar, and -scallop height methods are commonly utilized for applications involving continuous surfaces, but they may cause defects in cutting processes [29–32]. To generate accurate and computationally-efficient collision-free non-planar tool paths, tool path planning strategies based on conformal mapping have recently emerged [23–26]. For example, Sun *et al.* proposed a spiral tool path generation method based on conformal maps for machining on complex surfaces, which first converted the compound surface into triangular meshes and subsequently generated the tool path based on the inverse mapping of spirals to the 3D surface [26]. However, the algorithm was limited to surfaces free of holes and islands. This limitation was later addressed by developing a method to generate non-planar tool paths for trimmed surfaces based on conformal mapping with a free boundary [24]. Li *et al.* developed a non-planar tool path planning algorithm for machining on freeform surfaces based on

a least-squares conformal map (LSCM) on triangular meshes [25], which first mapped 3D triangular meshes to a 2D plane by LSCM parameterization [33] followed by tool path generation and analysis in a 2D parametric space. In addition to roughing operations, non-planar tool path planning is also the basis for machining smooth surfaces and finishing operations [34]. Further, non-planar tool path planning has enabled advances in non-contact manufacturing and inspection processes. For example, Phan *et al.* developed a non-planar tool path planning algorithm based on a conformal map approach to control overlapping for in-plane laser inspection operations [22]. Thus, the creation of non-planar tool path planning algorithms for emerging manufacturing processes, such as additive manufacturing processes, could expand process utility and improve final quality.

2.2 Tool Path Planning for Non-planar Additive Manufacturing

While 3D printed parts are typically fabricated using layered, planar tool paths generated from slicing programs, non-planar tool path planning has recently been examined for post-processing modification of such parts, including reinforcement, finishing, and repair operations. For example, curved-layer manufacturing (CLM), a method of using curved layers based on a ‘height grid’ instead of planar layers in model slicing and initially developed for laminated-object manufacturing (LAM) [35], has been used to mitigate defects associated with 3D printed parts fabricated using layered, planar tool paths (*e.g.*, ‘stair-stepped’ surface artifacts). For example, Chakraborty *et al.* introduced a potential CLM algorithm for fused filament fabrication (FFF) processes based on parametric surfaces [11]. To date, CLM has been used as a post-processing operation to improve the mechanical properties and surface finish of parts fabricated via FFF processes (*i.e.*, layered planar tool paths) [11–13,36–42]. While conformal FFF methods based on

CLM facilitate reinforcement and repair, they are limited regarding achievable tool path complexity and applications, as they primarily utilize commercially available thermoplastics, involve high temperatures, and are typically programmed within computer-aided design software based on slicing algorithms. For example, the tool paths generated by CLM are have been limited to zigzag-patterned filling paths and non-complex shell-type parts with parametric surfaces [11–13,36–41,43]. In addition to the zigzag patterned paths, McCaw and Cuan-Urquizo recently demonstrated a method for fabricating engineered lattices along Bezier surfaces on a pre-fabricated mandrel [42]. Lim *et al.* recently utilized CLM for extrusion-based 3D printing processes of concrete sandwich panels in large-scale construction applications [44], suggesting that conformal 3D printing can be applied beyond high-temperature extrusion-based 3D printing processes (*e.g.*, FFF processes).

In addition to FFF processes, which heavily rely on thermoplastics and CLM-based non-planar tool path planning approaches, microextrusion 3D printing processes have also leveraged non-planar tool path planning not only for reinforcement, repair, and finishing applications but also for the functional augmentation of parts (*i.e.*, including 3D printed features on an object or part that impart new functionalities). Thus, conformal microextrusion 3D printing has been examined in multiple applications that have involved objects of varying geometric and organic shape characteristics. Davis *et al.* proposed a microextrusion conformal printing method for encasing objects by generating layers between the boundaries of initial convex objects and desired geometric shapes in both 2D and 3D [45]. However, the proposed algorithm was not validated experimentally and was limited to convex initial shapes. Adams *et al.* used a microextrusion 3D printing process to fabricate 3D electrically small antennas across glass hemispheres with a radius

of curvature (R) of 12.7 mm by depositing single layer paths conducting silver nanoparticle-based inks through a 0.1 mm diameter nozzle (d) (*i.e.*, given the antennas spanned the full hemisphere, the path length (L_p) was comparable to R) [46]. Similarly, Vatani *et al.* printed $\sim 37 \text{ cm}^2$ multi-tactile sensors on a hemispherical polymer object of $R \sim 50 \text{ mm}$ using a $535 \text{ }\mu\text{m}$ diameter nozzle [9]. Kong *et al.* printed 7.07 mm^2 quantum dot light-emitting diodes on contact lenses of $R \sim 10 \text{ mm}$ using 108 to $210 \text{ }\mu\text{m}$ diameter nozzles [47]. We note that hemispheres are geometric objects that can be described by analytical expressions. In addition to conformal 3D printing on objects with geometric shape, such as hemispherical lenses, the demand for form-fitting and personalized wearable healthcare technology has exposed a need for conformal 3D printing on objects with organic shape, such as the human body or internal organs. Guo *et al.* recently used microextrusion 3D printing in which $d = 100 \text{ }\mu\text{m}$ to fabricate 16 mm^2 tactile sensors on human fingertips ($R \sim 30 \text{ mm}$) [48]. Singh *et al.* used conformal microextrusion 3D printing on kidney models ($R \sim 15 \text{ mm}$) in which $d = 0.6\text{-}1.2 \text{ mm}$ to fabricate 9 cm^2 organ-conforming microfluidic devices for non-invasive isolation and profiling of biomarkers during organ preservation studies [49]. Given $L_p \sim A_p^{1/2}$, a critical review of the aforementioned reported studies suggests that: 1) the ability to print tool paths of $L_p \sim R$ on surfaces with $R < 10 \text{ mm}$ remains a critical technical barrier on objects with organic shape (*e.g.*, the human body, internal organs, and form-fitting devices), and 2) limited studies exist for high quality conformal 3D printing on objects with geometric or organic shape based on point cloud representations of object geometry (*i.e.*, 3D data).

2.3 Tool Path Planning for In Situ Bioprinting

Three-dimensional (3D) bioprinting is an additive manufacturing technology which enables multi-material computer-aided fabrication of 3D constructs with complex geometries

using living cells, and biomaterials via layer-by-layer printing process [50,51]. 3D bioprinting facilitates the fabrication of biomimetic multi-layer tissues and scaffolds for regenerative medicine such as 3D printed skins and wound dressings [4,6,52]. Among the 3D bioprinting processes, which include stereolithography-, inkjet-, extrusion-based, and laser-assisted bioprinting, microextrusion processes have received considerable attention in regenerative medicine due to their compatibility with a wide range of bioink materials, including cellular, acellular and functional materials [3,53–55]. 3D bioprinting process starts with designing the 3D model of the biological construct or obtaining the computer-aided-design (CAD) model representing the organ geometry using reverse engineering techniques [55–59]. Traditionally, path planning for bioprinting is generated by slicing algorithms based on the CAD model of the desired construct and the fabricated constructs are then transferred to the target biological surface [4,50,51,60]. Reverse engineering has been increasingly utilized in medical applications to obtain 3D models of organs or other anatomical structures from computed tomography, magnetic resonance imaging, and ultrasound. These models have been used for fabrication of custom scaffolds, wound dressings and prosthetics [4,54,61–65]. Relatively fewer researchers, however, have addressed the challenge of direct printing on tissues and organs, which is referred to as *in situ* bioprinting [16]. The creation of novel *in situ* bioprinting processes can potentially address some of the translational barriers associated with 3D-bioprinted tissue scaffolds, including challenges associated with scaffold transfer and integration that may arise in traditional fabricate-and-transfer methods (*e.g.*, geometric mismatch of the scaffold or damage associated with handling during transfer and integration) [16–20]. Several researchers have demonstrated *in situ* bioprinting methods by using reverse engineering to capture the surface of the tissue. For example, Albanna *et al.* proposed a process

for *in situ* bioprinting of autologous skin cells for on-site accelerated wound management based on based on integrated laser scanner that obtained the surface features of the wound [16]. Ma *et al.* demonstrated *in situ* bioprinting on rabbits for cartilage regeneration using a 6-degree-of-freedom (6-DOF) robot and generated a layer-by-layer bioprinting path plan based on the defect geometry obtained by computerized tomography (CT) images [21]. Recently, Li *et al.* showed layer-by-layer *in situ* bioprinting of a photopolymerization bioink on pigs for repairing bone defects using 4-DOF robot and CT imaging [22]. While 3D printed biological constructs are typically fabricated using planar tool paths that are often generated by slicing software based on the CAD model of the target surface, non-planar tool path planning has recently been examined for *in situ* bioprinting conforming to the object surfaces. For example, Fortunato *et al.* proposed a 5-DOF robotic bioprinting platform to enable extrusion onto irregular surfaces through conformal path planning. Recently, Uzel *et al.* developed a multinozzle 3D printing platform to deposit multiple inks onto arbitrary surfaces using a line profilometer to scan the surface of interest [25].

In addition to the ability to direct tools across nonplanar substrates based on the 3D organic shape of anatomical structures (*e.g.*, limbs and organs), *in situ* bioprinting processes should enable mitigation of mechanical disturbances, such as associated with movement of the tissue (*e.g.*, caused by respiration) or tissue and tool movement caused by environmental disturbances (*e.g.*, background vibration). Further, *in situ* bioprinting may occur in settings that are prone to mechanical disturbance, such as vessels and aircraft. For example, the movement of astronauts and payloads in the International Space Station and the motion of the space station during attitude control generate transient vibrations in the medium frequency category ($10^{-3} - 1$ Hz) [35]. Thus,

there remains a demand for additive manufacturing processes for planar and non-planar material deposition in the presence of mechanical disturbances.

The growing interest in 3D bioprinting has increased the need for quality control processes to ensure the accuracy of the printed constructs [15,55,66–68]. Several researchers addressed the problem of quality analysis by generating quality prediction and assessment methods that are performed post process in various bioprinting techniques [69–71]. However, currently proposed processes are based on open-loop control with limited sensing capabilities. *In situ* bioprinting in a surgical setting is a comprehensive process that requires defect imagining, data processing, process planning and bioprinting to be performed consecutively to fabricate anatomically accurate constructs by depositing biomaterial onto the injury site following the curved geometric features of the tissue surface [5,68]. Therefore, it is important to incorporate sensing tools into the bioprinting process to control the process inputs based on the measured errors for accurate material deposition. For example, Armstrong *et al.* integrated a laser displacement sensor into the bioprinting system to control the reference machine path to improve the spatial material extrusion for the next print iteration [8,72]. However, previous work has been limited to the applications on stationary target surfaces. There have been limited studies in real time process control systems for 3D bioprinting on unconstrained and nonplanar surfaces in the presence of movement or mechanical disturbances in the workspace. O'Neill *et al.* attempted to ink-jet print hydrogels onto unconstrained human hand using a commercial hand tracking system and a depth sensing profilometer [73]. Zhu *et al.* demonstrated an adaptive extrusion-based 3D printing method to fabricate sensors on moving human hands using computer-vision and image-processing techniques

[74]. Later, Zhu *et al.* 3D printed a hydrogel-based sensor on a deforming porcine lung by combining offline machine learning methods and online computer-vision based control [75].

2.4 Tool Path Planning for Inspection

In addition to 3D printing, tool path planning is an integral part of inspection process planning. The need for automated inspection processes and inspection tools increases as the part complexity and variety increases. The manual inspection of the finished parts is both time consuming and subject to human error [17]. Hence, computer-aided inspection planning for touch-based probes and coordinate measuring machines (CMM) has been widely studied for automated inspections of manufactured parts [17]. The main constraint in inspection path planning is collision detection and automatic avoidance of obstacles since the sensing tool or tool holder may collide with the sample and damage both the tool and sample [17,20]. Various approaches have been proposed to generate collision-free scanning paths for CMMs [17–21]. For example, Zhao *et al.* combined a laser scanner and a touch-trigger probe to create collision-free inspection plans for CMM using the product and manufacturing information data contained in the computer-aided design (CAD) model of the part [18]. Later, Mineo *et al.* proposed a Mesh Following Technique to generate tool paths directly from the points on the tessellated model (*i.e.*, mesh) without curve fitting and approximation steps [19]. Recently, Liu *et al.* presented optimal path planning system that minimizes the total inspection time for freeform auto body surfaces using simulated annealing-based optimization algorithm [20].

The collision-free path planning techniques could be extended to inspection of biological constructs and organs. Recent developments in biotechnology have shifted the focus of inspection

from cellular-level to organism-level biological systems including mesoscopic (*i.e.*, millimeter to centimeter) and macroscopic tissues and organs [76–78]. The applicability of microscopic imaging techniques to the inspection of large tissues is limited because of the strong absorption and scattering of light by the large biological samples [79]. Therefore, there is a need for the development of new automated inspection techniques that enable the characterization of large biological specimens. Biosensors are among the most widely used inspection methods for biological samples since they enable high-throughput screening, real-time analysis, and label-free detection [80–82]. Over the past decades, biosensors have been used for diagnostics, screening, and process control in various industries such as biomedicine [83], agriculture [84], and food safety [85]. Electrical impedance-based biosensing methods has emerged as an attractive noninvasive inspection approach for monitoring cell viability [86], type [87], differentiation [88], chemosensitivity [89], and organ assessment [90] through electrical properties of biological samples. Thus, the impedimetric sensing approach could be leveraged for automated inspection of macroscopic biological samples.

Ensuring the quality and safety of macroscopic tissue-based products are essential in various areas including the food industry, tissue engineering, and organ transplantation. In the food industry, bioimpedance-based sensing technology has been leveraged for the assessment of food quality and safety since it enables monitoring of physiological conditions of animal and plant tissues [91,92]. Furthermore, as 3D bioprinting is the next phase in personalized medicine, tissue characterization challenges will inevitably be an issue that needs to be addressed [93,94]. Real-time and non-invasive inspection methods can help accelerate the clinical applications of 3D bioprinted tissues and organs. Organ transplantation is another potential application area for

biosensing, where inspection of macroscale biological constructs is needed. Lack of quantitative and accurate organ inspection methods is one of the challenges that contribute to organ shortage and transplant inefficiency [95]. However, CAD or mesh models containing the topographic information of the part are required inputs for the inspection planning processes. Reverse engineering (RE) techniques, such as 3D scanning, computed tomography and magnetic resonance imaging, have been utilized to obtain 3D models of organs or other anatomical structures in the absence of an existing CAD model [61,63,64,96,97]. Thus, new methods for inspection path planning that synergize with 3D scanning-based reverse engineering workflows could enable the characterization of macroscale tissues and organs with freeform surfaces.

3 Conformal 3D Printing of Non-planar Antennas on Wrinkled and Folded Kapton Films using Point Cloud Data

We report a novel reverse engineering-driven method for conformal microextrusion 3D printing of functional materials on complex three-dimensional (3D) structures and thin films of near-arbitrary topography. A non-planar tool path programming algorithm for conformal microextrusion 3D printing based on point cloud data representations of object geometry is presented. We show that the optimal nozzle-substrate standoff distance for quality 3D printing depends on the substrate’s local geometric features (*i.e.*, path slope and curvature) and the tool trajectory. The impact and utility of the novel conformal microextrusion 3D printing process were demonstrated by fabrication of 3D spiral and Hilbert-curve loop antennas on various non-planar substrates, including wrinkled and folded Kapton films and origami. 3D-printed conformal antennas exhibited resonant frequencies ranging from 1.5 – 2.7 GHz with S_{11} less than 10 db. This work provides a new method for conformal 3D printing on one-of-a-kind objects and non-planar films.

3.1 Introduction

Flexible and conformal electronics are the basis of various emerging devices and technologies, including wearable electronics [98–102], electronic skins [103–107], bionic devices [108–110], soft robots [111–114], and the Internet of Things (IoT) [115–117]. For example, conformal antennas are receiving considerable interest based on extensive healthcare [118–124], IoT [125–127], and aerospace applications [128–130]. Various printing techniques have been utilized for the fabrication of flexible antennas, including screen-printing [131,132], inkjet printing [133–135], and liquid metal-filled microfluidics [136,137]. These techniques have enabled

antenna fabrication on planar flexible substrates, such as polyethyleneimine (PEI) [138,139], polyethylene terephthalate (PET) [140–142], and polydimethylsiloxane (PDMS) [143,144].

Various processes have been utilized for antenna fabrication on curved substrates [145–148]. The most common techniques to fabricate curved antennas include manual forming and coating processes, tiling of planar elements on curved surfaces, or use of flexible substrates [145,147]. Soft lithography processes have also been applied for the fabrication of conforming antennas given the deformability of plastic stamps. The use of coating processes (*e.g.*, transfer printing), flexible substrates, and additive manufacturing processes now represents the state of the art for conformal antenna fabrication [149–152]. While ‘fabricate-and-form’ techniques offer considerable promise, the electronic components may be subjected to strain during forming, which constrains device material selection. For example, conformal antenna performance can be adversely affected by substrate deformation and result in a degradation of radiation characteristics [153–155]. Hence, additive manufacturing processes enabling antenna fabrication on non-planar substrates, particularly thin films, and complex 3D objects may considerably expand antenna design opportunities (*e.g.*, regarding material selection and substrate integration).

Additive manufacturing processes potentially offer the ability to overcome limitations of applying transfer printing for conformal antenna fabrication, such as the need for mask fabrication and challenges with substrates that exhibit sharp edges [145]. The use of shape-memory and photoactive polymers for self-assembly-based techniques is also receiving considerable attention [148,156,157]. In addition to the self-assembly technique, 3D printing has been utilized to manufacture support structures for manual antenna assembly as well as to fabricate curved antennas by direct-write applications [145–147]. Selective laser sintering and fused-deposition

modelling techniques have been used to fabricate the support structure on which antennas were designed [158,159]. Alternatively, 3D inkjet printing, 3D aerosol jet printing and microextrusion printing techniques have been utilized for direct-write applications to fabricate 3D conformal antennas. Direct-write methods are efficient and offer a mask-free fabrication approach [145,147,160]. Microextrusion printing processes also enable the utilization of a broad range of functional inks [145–147]. For example, Adams *et al.* demonstrated the conformal 3D printing of electrically small antennas on a glass hemisphere using a bent nozzle and silver nanoparticle ink [46].

Processes that enable material deposition on one-of-a-kind substrates (*e.g.*, complex geometric and freeform objects, thin films, textiles or anatomical structures), are central to various industries, including additive manufacturing, electronics manufacturing, and biomanufacturing. A reverse engineering (RE) process generates a 3D model of an object based on measurements obtained from non-contact or contact-based tools, such as coordinate measuring machines or laser scanners, respectively [96,97]. RE has been used to obtain computer-aided-design (CAD) models for three main purposes: to manufacture a sculpted model or an existing object, to repair a damaged or defective part, or to control the quality of the manufactured part by using offline and online methods. Given CAD models are required inputs for the majority of milling and additive manufacturing applications, RE is required in the absence of an existing CAD model [96,97,161,162]. Reverse engineering techniques, such as 3D scanning, are now being employed in additive manufacturing applications in which the creation of a CAD model for a part may be time-consuming or challenging, which is common among applications involving parts with complex non-planar geometry (*e.g.*, wearables, electronic textiles, form-fitting devices, anatomical

models). Traditionally, path planning for 3D printing is generated by slicing algorithms, which require a CAD model as an input [11,161,162]. RE has been increasingly utilized in medical applications to obtain 3D models of organs or other anatomical structures from computed tomography, magnetic resonance imaging, and ultrasound [61–64]. These models have been used for preoperative surgical planning, training, and fabrication of custom prosthetics [61–64]. RE is also used to capture the geometry of the defected parts for repair and remanufacturing [163,164]. For example, the integration of metal 3D printing technologies and RE allows for a faster repair technology that can extend the life of aircrafts, ships and vehicles [165,166]. Thus, new methods for fabrication of conformal electronics that synergize with 3D scanning-based reverse engineering workflows could enable the fabrication of novel antennas, such as on high performance engineering materials (*e.g.*, polyimide films).

Here, we provide a new method for conformal electronics 3D printing on one-of-a-kind substrates based on point cloud data representation of object geometry. This method provides a versatile approach for functional material printing on polymer thin films that exhibit random non-planar topography. Our point cloud-based path planning (PCPP) algorithm enables conformal microextrusion 3D printing of user-defined planar tool paths across one-of-a-kind substrates, including complex geometric objects and wrinkled and folded Kapton films and origami. We also provide new insights into the origin of common conformal 3D printing defects, including tool-surface contact. The utility of the process for conformal electronics 3D printing was demonstrated by the fabrication of conformal spiral coil, Hilbert-curve loop, and triangular monopole antennas on Kapton films and origami that contain various random topographical features (*e.g.*, wrinkles and folds). 3D-printed conformal antennas on folded and wrinkled Kapton films and origami were

characterized through S_{11} frequency response. These prototypic 3D-printed conformal antennas on polyimide thin films suggest that reverse engineering techniques can support the design and additive manufacturing of novel printed 3D electronics on non-planar thin films.

3.2 Materials and Methods

3.2.1 Materials

Cellulose nanofibrils were from UMaine PDC. Polylactic acid (PLA) filament was from LulzBot. Conductive silver epoxy (AA-DUCT 907) was from Atom Adhesives. Kapton tape (polyimide film) was from Uline. Pluronic F-127 was from Sigma-Aldrich.

3.2.2 Design and Fabrication of Test Parts

The test part ($80 \times 80 \text{ mm}^2$) used for characterization of the PCPP algorithms was created using a computer-aided design (CAD) and 3D graphics software (Rhino 6; Rhinoceros 3D).

3.2.3 Point Cloud Generation for Reverse Engineering-driven Non-planar Tool Path Planning

Prior to 3D scanning, three user-defined reference points ($\sim 1 \text{ mm}$ diameter) were placed around the perimeter of the object using a black marker to provide reference points for the 3D printing frame. The object was then scanned using a calibrated single camera-projector structured-light scanning system (HP 3D Structured Light Scanner Pro S2; HP) to acquire the point cloud data following our previously reported protocols [47,49,167,168]. Briefly, the point cloud data was converted into a triangulated mesh file using the vendor-provided software, which provided one of three inputs to the PCPP algorithm (the other two inputs being the reference points for the 3D printing reference frame and the user-defined planar tool path).

3.2.4 Generation of the Scanning Reference Frame

The PCPP algorithm commenced with a registration process that aligned the 3D scanning-generated point cloud data ($\mathbf{S}$; $n \times 3$) and user-defined path data ($\mathbf{T}$; $m \times 3$) to the 3D printing reference frame. The spatial coordinates of the three user-defined reference points on the object were identified as the centroids of the associated holes in the mesh structure. The area centroid of each reference point, which served as the user-defined reference point in the 3D scanning reference frame, was first calculated using the ‘hole edge’ selection tool within the graphics software (Rhino 6). This identified the vertices that defined the hole perimeter and area centroid location. Thus, $\mathbf{S}^r = [S^r_1, S^r_2, S^r_3]$, a 3×3 matrix, generated from the point cloud data provides reference points for registration of user-defined path data with the process reference frame (*e.g.*, object on an additive manufacturing system stage). $S^r_i = [x_i, y_i, z_i]$ are the x -, y -, and z -coordinates of the i^{th} area centroid (*i.e.*, the i^{th} user-defined reference point in the scanning reference frame).

3.2.5 Generation of User-defined Tool Path Data in the Scanning Reference Frame

The user-defined 2D path was next defined to scale adjacent to the point cloud representation of the substrate (*e.g.*, object or thin film) using the drawing commands (*e.g.*, line, polyline, curve, circle, and ellipse) in Rhino 6 within the same graphic user interface. User-defined paths were discretized to generate motion commands capable of resolving the path using the ‘divide curve’ command. The path density was determined by the metric of two path points per nozzle diameter (d) (*i.e.*, paths contained $n = 2L_p/d$ points, where L_p is the total length of the user-defined path). Following final scaling and placement of the path above the intended printing area on the substrate’s point cloud data, the user-defined planar tool path was then projected in the z -direction onto the substrate’s surface (point cloud representation) using the ‘project’ command in

Rhino 6. The output of this process was an array of tool path points that corresponds to the user-defined tool path design in the scanning reference frame, which we refer to as the ‘virtual’ zero-tool standoff path, T . For the case of multiple disconnected tool paths, T is a nested array.

3.2.6 *Generation of the Process (Physical) Reference Frame*

Following the generation of S , S^r and T , the reference points associated with the 3D printing reference frame were generated. Prior to the generation of the reference points in the 3D printing reference frame, the object was first fixed on the stage of the 3D printing system. The part was not moved following this step until completing the 3D printing process. The spatial coordinates of the three user-defined reference points in the 3D printing reference frame (P ; $P = [P_1, P_2, \text{ and } P_3]$), a 3 x 3 matrix, were taken as the x, y, z -coordinates of the motion controller when the microextrusion nozzle was positioned at the center of the reference point within $0.05d$ from the surface (which avoided potential damage to the nozzle or object). Thus, P exhibits the same structure as S^r . The ordering of reference points in P should correspond to that of S^r . This process resulted in six reference points (three per reference frame) associated with the two reference frames, the 3D scanning and the 3D printing frames.

3.2.7 *Generation of Zero-offset Non-planar Tool Path Data in the Process Reference Frame*

The reference points for each reference frame, which create two 3 x 3 matrices (S^r and P), were next used to calculate transformation matrices that enable registration of the user-defined tool

path data to the object in the process reference frame. This resulted in a ‘physical’ zero-standoff path $\mathbf{T}^a$.

The point cloud data ($\mathbf{S}$) and the user-defined projected path data ($\mathbf{T}$) were first aligned to the 3D printing reference frame ($\mathbf{P}$) through the following rigid transformations that depend on the matrices $\mathbf{S}^r$ and $\mathbf{P}$ as:

$$(\mathbf{S}^a)^T = \mathbf{G}(\mathbf{S})^T \quad (1)$$

$$(\mathbf{T}^a)^T = \mathbf{G}(\mathbf{T})^T \quad (2)$$

The transformation matrix ($\mathbf{G}$) is defined as [40]:

$$\mathbf{G} = \mathbf{t}(P_2)\mathbf{R}_2(v_2, \theta_2)\mathbf{R}_1(v_1, \theta_1)\mathbf{t}(-S_2^r) \quad (3)$$

where $\mathbf{t}(\mathbf{u})$, a translation matrix that translates a point cloud by a vector $\mathbf{u}$, is given as:

$$\mathbf{t}(\mathbf{u}) = \begin{bmatrix} 1 & 0 & 0 & u_x \\ 0 & 1 & 0 & u_y \\ 0 & 0 & 1 & u_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

and $\mathbf{R}(\mathbf{u}, \theta)$, a rotation matrix that rotates a point cloud by an angle θ about the axes defined by a unit vector $\mathbf{u}$, is given as:

$$\mathbf{R}(\mathbf{u}, \theta) = \begin{bmatrix} \cos \theta + u_x^2(1 - \cos \theta) & u_x u_y(1 - \cos \theta) - u_z \sin \theta & u_x u_z(1 - \cos \theta) + u_y \sin \theta & 0 \\ u_y u_x(1 - \cos \theta) + u_z \sin \theta & \cos \theta + u_y^2(1 - \cos \theta) & u_y u_z(1 - \cos \theta) - u_x \sin \theta & 0 \\ u_z u_x(1 - \cos \theta) - u_y \sin \theta & u_z u_y(1 - \cos \theta) + u_x \sin \theta & \cos \theta + u_z^2(1 - \cos \theta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

where $\mathbf{v}_1 = \frac{\hat{\mathbf{a}}_1 \times \hat{\mathbf{b}}_1}{\|\hat{\mathbf{a}}_1 \times \hat{\mathbf{b}}_1\|}$, $\theta_1 = \arccos(\hat{\mathbf{a}}_1 \cdot \hat{\mathbf{b}}_1)$, $v_2 = \mathbf{R}_1 \hat{\mathbf{a}}_1$, $\theta_2 = \arccos((\mathbf{R}_1 \hat{\mathbf{a}}_2) \cdot \hat{\mathbf{b}}_2)$, $a_1 = \overrightarrow{S_2^r S_1^r}$,

$b_1 = \overrightarrow{P_2 P_1}$, $a_2 = \overrightarrow{S_2^r S_3^r}$, $b_2 = \overrightarrow{P_2 P_3}$, and $\hat{\mathbf{a}}_1$ and $\hat{\mathbf{b}}_1$ represent the normalized vectors a_1 and b_1 as

$a_1/\|a_1\|$ and $b_1/\|b_1\|$, respectively. A row of ones was added to the transpose of the matrices $\mathbf{S}$ and $\mathbf{T}$ to provide dimensional accuracy for matrix multiplication and was removed after the calculation. The outputs of this step in the algorithm were processing reference frame-aligned mesh data $\mathbf{S}^a$ ($n \times 3$) and user-defined zero-standoff path data $\mathbf{T}^a$ ($m \times 3$). The pseudo-code, Algorithm 1, is provided in Supporting Information (see Section 3.6). Example matrices for $\mathbf{S}^r$ and $\mathbf{P}$ are provided in Table S3.1 of Supporting Information (see Section 3.6).

3.2.8 *Generation of Non-planar Tool Path Data in the Process Reference Frame for Conformal Microextrusion 3D Printing*

Given conformal microextrusion 3D printing requires a gap between the microextrusion tool and the surface, the non-planar tool path $\mathbf{T}^a$ was then offset from the surface by modifying the vertical and lateral position of each coordinate in the path (*i.e.*, the x -, y - and z -coordinates) based on the tool geometry, the tool trajectory, and the topographical features of the substrate (*e.g.*, object) as defined by point cloud data, including the object slope and curvature. Specifically, the PCPP algorithm utilizes the nozzle inner diameter d , nozzle outer diameter d_o , the zero-standoff tool path $\mathbf{T}^a$, and the point cloud data representation of the object $\mathbf{S}^a$ as input parameters. The developed algorithm was implemented using the RhinoScript tool of Rhinoceros 6 software. The algorithm commenced by fitting a Non-Uniform Rational B-Spline (NURBS) curve of the degree three, $\mathbf{r}(t)$, through the points in $\mathbf{T}^a$ to calculate the tangent and curvature associated with the path points in $\mathbf{T}^a$ [169]. The curve, $\mathbf{r}(t)$, was generated using the “CurveThroughPt” command. The tangent $\mathbf{t}_i$ ($m \times 3$) and normal $\mathbf{N}_i$ ($m \times 3$) vectors were calculated using the “CurveTangent” and “CurveNormal” commands, respectively. The curvature κ_i at each point in $\mathbf{T}^a$ was calculated using the “CurveCurvature” command. The inflection points of the curve were obtained as the locations

where $\kappa_i = 0$ from the best-fit curve. The sign of the curvature was used to identify the z-coordinate direction of the curvature vector, which was negative for concave down surface profiles and positive on the concave up profiles. The tool trajectory $\mathbf{V}_i$ ($m \times 3$) was determined by using x and y axes values of $\mathbf{t}_i$. The z-coordinate of each path point was subsequently vertically shifted by a value of d . The algorithm then added a circle (C_i) with a diameter of d_o at each path point to simulate the nozzle location during printing and checked for an intersection between the circle and the point cloud data representing the surface. Thus, if the algorithm detected potential tool-surface contact as indicated by comparing the nozzle and surface locations, it translated the path point (T_i^a) laterally from the surface by L_i in the direction of $\mathbf{Q}_i$ to avoid contact between the nozzle and the surface. L_i was calculated as the distance required to achieve $d_o/2$ gap between the center of the nozzle tip and the surface, including a user-defined tolerance that provided a safety gap between the nozzle and surface. The tolerance was set to 0.1 mm throughout this study.

$$L_i = d_o/2 - |T_i^a, p_i| + tolerance ; \quad (6)$$

$$\mathbf{Q}_i = \overrightarrow{p_i, T_j^a} \quad (7)$$

where p_i is the centroid of the intersection points list $\{C_i \cap \mathbf{S}^a\}$. Next, the PCPP algorithm checked if the slope exhibited a downward trajectory as indicated by a negative z-coordinate value of the tangent vector. If $\mathbf{t}_i$ was downward, the algorithm added a lateral offset (M_i) to the tool path point (T_i^a) in the direction of $\mathbf{V}_i$, where M_i was calculated as:

$$M_i = 0.5d(1 + d\kappa_i) \quad for \quad \kappa_i \leq 1/d \quad (8)$$

$$M_i = d \quad for \quad \kappa_i > 1/d \quad (9)$$

The corrected tool path $\mathbf{T}^{a*}$ was calculated based on three cases determined by the tool-object intersection and tool trajectory:

Case1: There exists an intersection between C_i and S^a and $t_{i,z} > 0$.

$$T_j^{a*} = T_j^a + L_i Q_i \quad (10)$$

Case2: There exists an intersection between C_i and S^a and $t_{i,z} < 0$.

$$T_i^{a*} = T_i^a + L_i Q_i + M_i V_i \quad (11)$$

Case3: There exists no intersection between C_i and S^a and $t_{i,z} < 0$.

$$q_i \in \{|T_i^a, T_i^a - dV_i| \cap S\} \quad (12)$$

$$M'_i = \frac{d_o}{2} - |T_i^a, q_i| + M_i \quad (13)$$

$$T_i^{a*} = T_i^a + M'_i V_i \quad (14)$$

The pseudo-code, Algorithm 4, is provided in Supporting Information (see Section 3.6). The output of the PCPP algorithm was a user-defined non-planar tool path for conformal microextrusion 3D printing corrected for tool geometry, tool trajectory, and substrate geometry (slope and curvature), referred to hereinafter as $\mathbf{T}^{a*}$. The non-planar path was then described as motion control data using g-code.

3.2.9 Computational Characterization of Conformal Printing Quality

Prior to the 3D printing, the resulting filament thickness associated with the generated tool path was assessed with CAD and 3D graphics software. Using the 3D model of the test part obtained by 3D scanning and the tool path, which was the output of the algorithm, the trajectory of the path in reference to the user-defined tool path was examined by visualization of $\mathbf{T}^{a*}$ and S^a in the graphic user interface. The thickness of the filament was calculated as the distance between

the surface and the location of the nozzle reference point, which is defined as the back of the nozzle tip based on the printing direction. The nozzle reference point was determined by considering the outer diameter while moving downwards and the inner diameter in all other cases. To simulate a continuous filament, a NURBS curve was fit through the nozzle reference points using the “curve through points” command on the software. The filament thickness was measured as the distance between the nozzle reference curve and the surface in the direction of the surface normal vectors with intervals of $d/2$. The error was calculated as the difference between the measured thickness at each point along the tool path and the expected thickness, which was taken as the nozzle diameter d . Thus, the error exhibited both positive and negative values. The pseudo-code of the analysis is provided in Algorithm 5 of Supporting Information (see Section 3.6).

3.2.10 Conformal Microextrusion 3D Printing on a Test Part

Conformal microextrusion 3D printing on the test part was done using a custom microextrusion 3D printing system, which included a three-axis robot (MPS75SL; Aerotech), a digital pressure regulator (Ultimus V; Nordson), and a motion controller (A3200; Aerotech). 3D printing on the test parts was performed using a 30 wt% Pluronic F-127 hydrogel that contained 10 wt% cellulose nanofibrils with an added contrast agent. Inks were printed on the test part via the user-defined tool path using a 20-gauge tapered tip ($d = 603 \mu\text{m}$), extrusion pressure of 13.2

psi, and printing speed of 5 mm/s. The density of the paths was 3.33 points/mm based on the aforementioned path discretization metric.

3.2.11 Experimental Analysis of Conformal Printing Quality

The quality of printed material (test traces) on the test part was characterized by image analysis. Photographs of the printed traces were acquired by using a digital camera (D7200; Nikon) immediately following the conformal 3D printing process. Each printed trace of the 1D line path was analyzed using image analysis software (ImageJ; NIH) and CAD software. The expected width was taken as d along the non-planar path. The error was defined as the difference between the measured filament width along the path and the expected width. Thus, the error exhibited both positive and negative values.

3.2.12 3D Printing of Conformal Antennas on 3D Structures with Complex Geometry

3D models associated with dimpled-hemisphere and polyhedral 3D structures were designed using CAD software. The 3D spiral antenna path was designed based on reported designs [170]. Conductive silver epoxy was conformally printed using the PCPP algorithm on the substrates with a custom microextrusion 3D printing system (Aerotech) in the user-defined 3D spiral antenna path (556 mm; 1853 points) with a 20-gauge tapered tip ($d = 603\mu\text{m}$), extrusion pressure of 9 psi, and printing speed of 2.5 mm/s.

3.2.13 3D Printing of Conformal Antennas on Non-planar Kapton Thin Films and Origami

Flat Kapton films, which provided the basis of all Kapton substrates examined in this study, were prepared by depositing parallel strips of Kapton tape on a paper substrate. Wrinkled, folded, and origami films and structures were prepared as follows. Folded Kapton star-like structures

were inspired by reported folding patterns [171]. Randomly wrinkled Kapton films were prepared by manual forming of an initially flat Kapton film into a sphere followed by partial flattening. Kapton origami cranes were prepared based on reported methods (<https://www.origami.me/crane/>). Conformal antennas were printed with a 20-gauge taped nozzle (Nordson) using the aforementioned microextrusion 3D printing system at a speed of 3 mm/s and extrusion pressure of 7 psi. The 3D-printed antennas were subsequently cured at room temperature for 24 hours.

3.2.14 Characterization of the Conformal Antenna

SubMiniature version A (SMA) connectors were bonded to the 3D-printed antennas using conductive epoxy. The antennas were designed to be 50 Ω nominal. The S_{11} frequency responses of the 3D-printed conformal antennas across the 0 to 3 GHz frequency range with respect to 50 Ω were measured using a spectrum analyzer (FSH6, Rohde & Schwarz) with a VSWR bridge (FSH-Z2, 10 MHz to 3GHz, 50 Ω ; Rohde & Schwarz). Prior to measurements, the system was calibrated with a standard calibration kit.

3.3 Results

3.3.1 PCPP Algorithm Characterization using a Test Part

As shown in Figure 3.1, the PCPP algorithm generates non-planar tool path data for conformal microextrusion 3D printing based on point cloud representations of substrate geometry. Point cloud data collected via object 3D scanning and user-defined planar tool path data is used to generate a corresponding non-planar tool path across the object's surface (see Figure 3.1a). As shown in Figure 3.1b, point cloud representations of the object's local geometry and the tool

trajectory are used to determine a tool path for quality conformal 3D printing (*i.e.*, a tool path that results in the controlled deposition of a filament of material with consistent width and height). Given that object geometry may vary among conformal 3D printing applications, the PCPP algorithm was validated using a test part that exhibited a range of geometric features, including regions of discontinuous and infinite slope as well as features with a radius of curvature R ranging from $0.4d$ to ∞ (*i.e.*, constant slope) (see Figure S3.1).

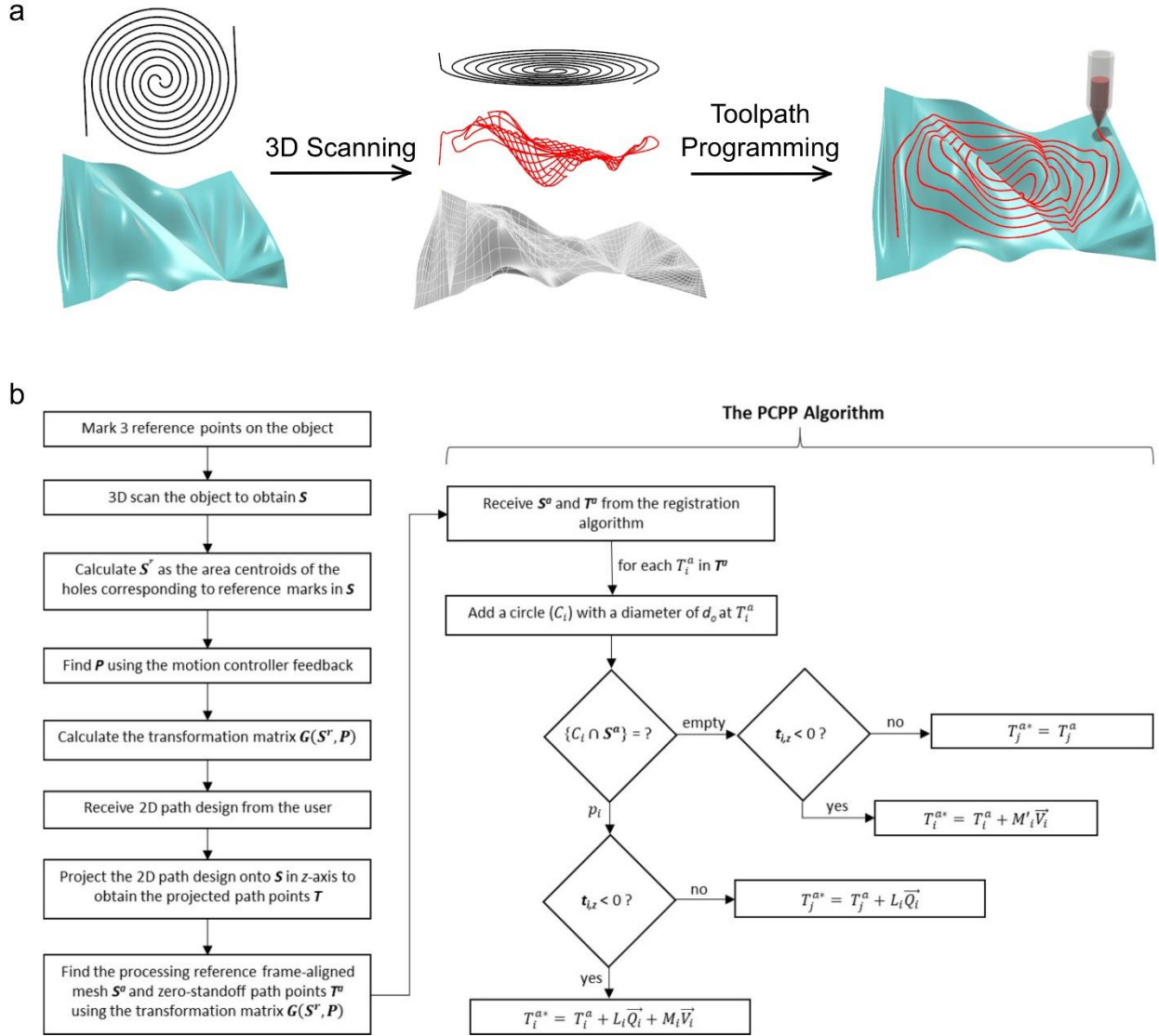


Figure 3.1 Illustration **(a)** and flowchart **(b)** of the point cloud-based path planning (PCPP) algorithm for conformal microextrusion 3D printing on one-of-a-kind substrates.

As shown in Figures 3.2a and b, the user-defined reference points on the test part created holes in the point cloud. Figure 3.2b highlights the area centroid calculation block of the PCPP algorithm, which identifies the spatial coordinates associated with the scanning reference frame

points (S^r). Figure 3.2c highlights the process of identifying the spatial coordinates associated with the same reference points but in the 3D printing reference frame (P). Single-layer 2D user-defined planar tool paths consisting of lines were used to evaluate the PCPP algorithm (see Figure 3.2d). As shown in Figure 3.2e, the output of the alignment-projection block of the PCPP algorithm was the scanning data aligned to the 3D printing reference frame (S^a) and the physical zero-standoff tool path (T^a), which is also aligned to the 3D printing reference frame.

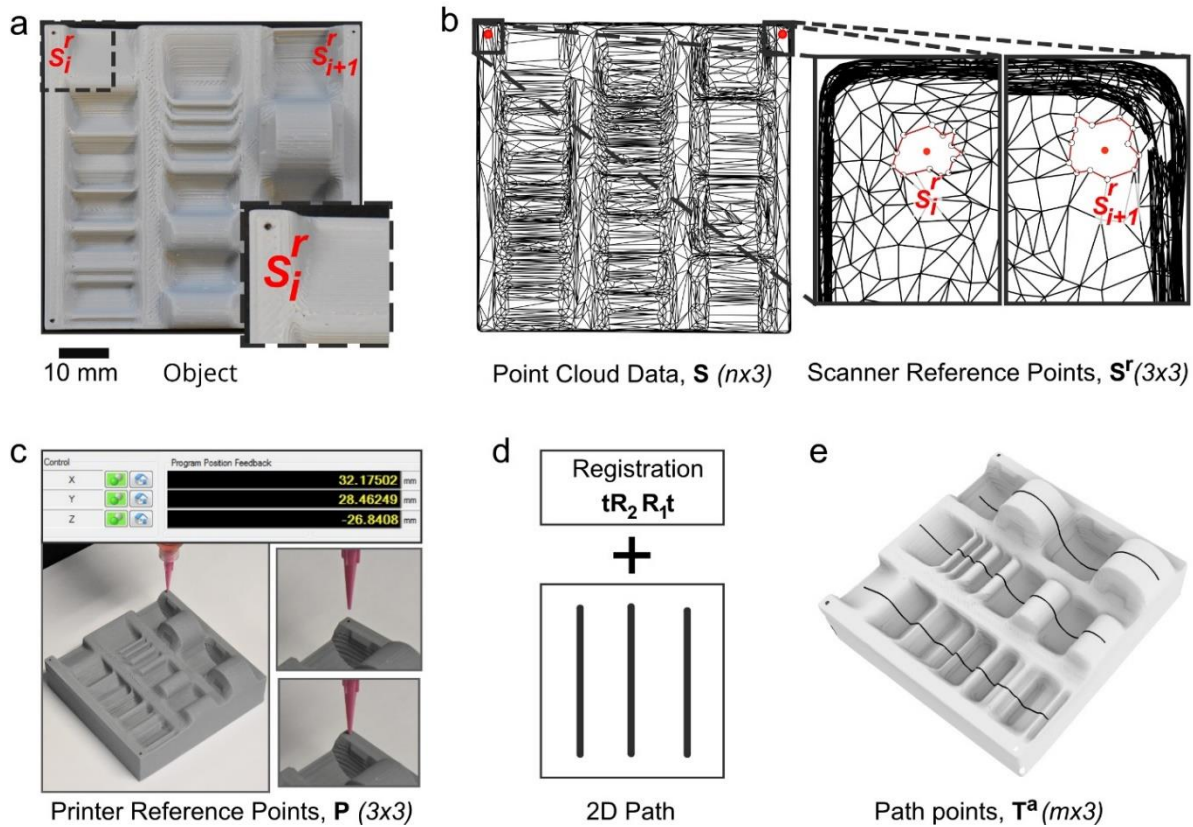


Figure 3.2 Photograph of the test part for algorithm characterization depicting the user-defined reference points. **b)** Point cloud data from the object (S). Reference points associated with the 3D scanning reference frame (S^r) were obtained as the centroid of the hole created in the point cloud data by each user-defined reference point (point cloud data is decimated for purposes of illustration). **c)** Photograph of the process for generating corresponding reference points in the 3D

printing reference frame ($\mathbf{P}$) using the 3D printer's position as obtained through a three-axis motion controller. **d)** Illustration of the inputs to the PCPP algorithm. The transformation matrix obtained from the alignment of $\mathbf{S}^r$ and $\mathbf{P}$ combined with user-defined planar tool path data enables the generation of a physical zero-standoff tool path ($\mathbf{T}^a$) (**e**). Scale bars = 10 mm.

3.3.2 Analysis of Conformal Microextrusion 3D Printing Quality using the PCPP Algorithm

As shown in Figures 3.3a-b, the PCPP algorithm modifies the vertical and lateral positions of each coordinate in the projected path $\mathbf{T}^a$ based on the tool geometry, tool trajectory, and object topographical features, and generates the tool path $\mathbf{T}^{a*}$ to be used in conformal 3D printing. The algorithm exhibited a tool path $\mathbf{T}^{a*}$ of different lengths, local surface normal vectors and curvatures than the projected path $\mathbf{T}^a$ (see Figure 3.3b). As shown in Figures 3.3c-g, the PCPP algorithm mitigated the majority of flattening and floating artifacts and avoided the tool-surface contact defect found in the absence of topographical correction (see Section 3.6) and achieved quality deposition across all regions of the test part. Scaling the lateral offset by the relative curvature value across the intended printing path achieved relatively improved mitigation of the floating artifact, which primarily occurred at the inflection points in the absence of curvature correction. Deviation in the filament path by d was still observed during downward tool motion on surfaces with negative curvature (*i.e.*, concave down surfaces; see Region 3). As shown in Figure 3.3d, the PCPP algorithm resulted in a near-uniformly distribution of errors across the path, which is attributed to random error in the process. These results suggest that the PCPP algorithm was capable of mitigating tool trajectory- and shape-dependent defects associated with conformal microextrusion 3D printing processes using an orthogonal three-axis robot. The conformal 3D

printing quality achieved by the PCPP algorithm was compared with the two control path planning algorithms in Figures 3.3e-g. The control path planning algorithms were two simplified versions of the PCPP algorithm: 1) a PCPP algorithm that involved no path corrections for tool trajectory or object topography, and 2) a PCPP algorithm that involved corrections for tool trajectory and object slope, but no path corrections for object curvature. The description and analysis of the control algorithms are provided in the Supporting Information (see Section 3.6).

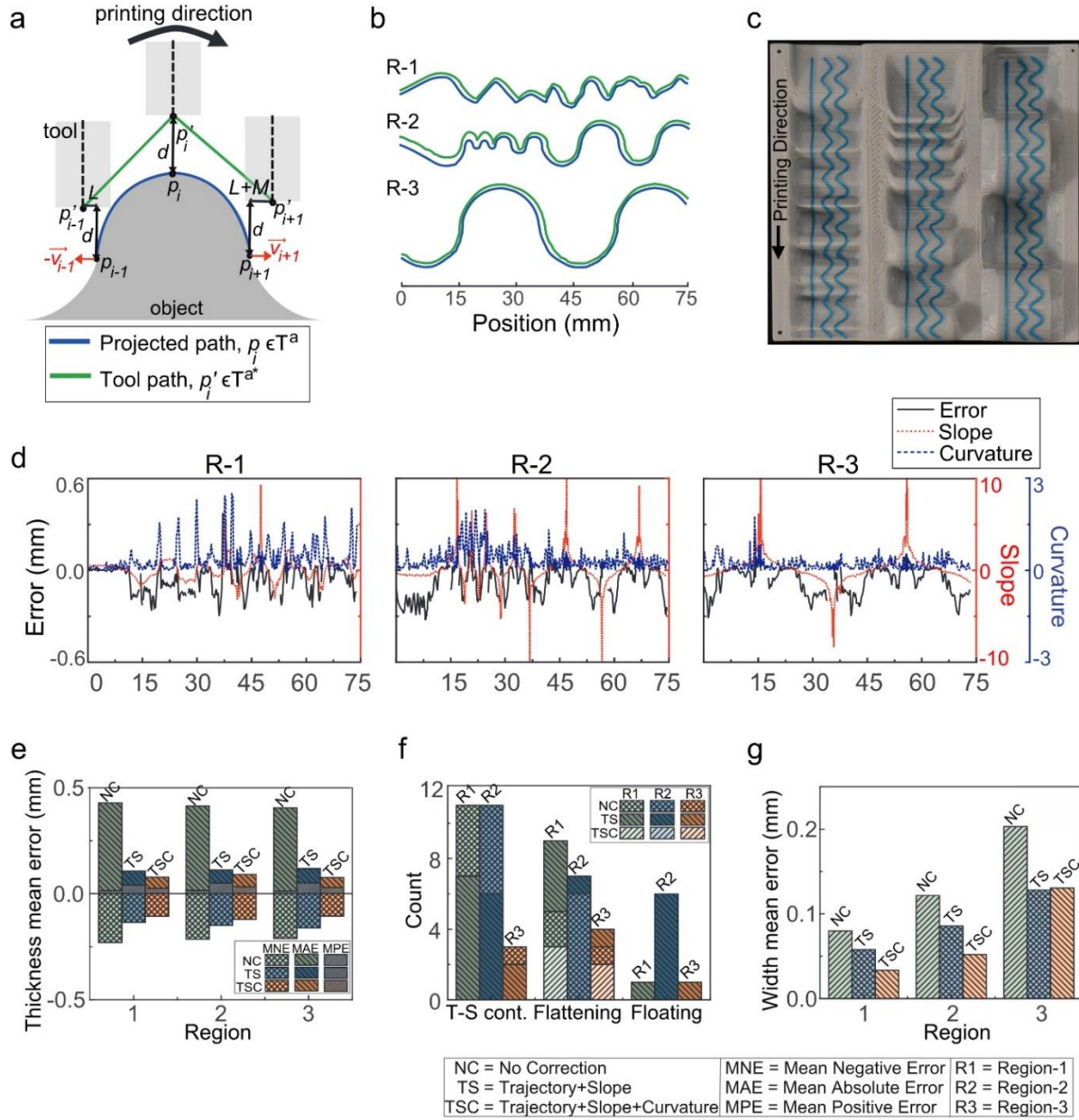


Figure 3.3 **a)** Illustration of the point cloud-based path planning (PCPP) algorithm for conformal microextrusion 3D printing on one-of-a-kind substrates with complex geometry. **b)** Visualization of the resultant non-planar tool path on the three regions of the test part (an offset distance of $d = 2$ mm was utilized for illustration). **c)** Photograph of the resultant print quality from a top-down perspective. **d)** CAD analysis of non-planar 3D printing quality in terms of the error in the expected filament thickness vs. the local slope and curvature of the object. **e)** Comparison of

algorithm performance in terms of the mean absolute error, mean negative error, and mean positive error in the expected filament thickness. **f)** Comparison of algorithm performance in terms of the prevalence of tool-surface (T-S) contact, flattening, and floating defects. **g)** Comparison of non-planar tool path planning algorithm performance on the mean absolute error in the measured filament width.

3.3.3 *Microextrusion 3D Printing of Conformal Antennas on 3D Structures of Complex Geometry*

In Figure 3.4, we show that the PCPP algorithm enables the fabrication of novel conformal spiral antennas on geometrically complex substrates, including polyhedron and non-developable surfaces. The change in z-axis direction of the tool path (*i.e.*, the height of the printed antenna) was 13.4 and 9.61 mm, the maximum angle of inclination was 54.8 and 50.8°, and the minimum radius of curvature, R , was 0.24 and 0.14 mm for the dimpled-hemisphere and the polyhedron surface, respectively. The fabrication approach is highlighted in Figures 3.4a-d and f-i. Figures 3.4e and j show that the resonant frequency of the 3D-printed spiral antenna on the dimpled-hemisphere and polyhedron surface was 0.8 and 2.0 GHz, respectively.

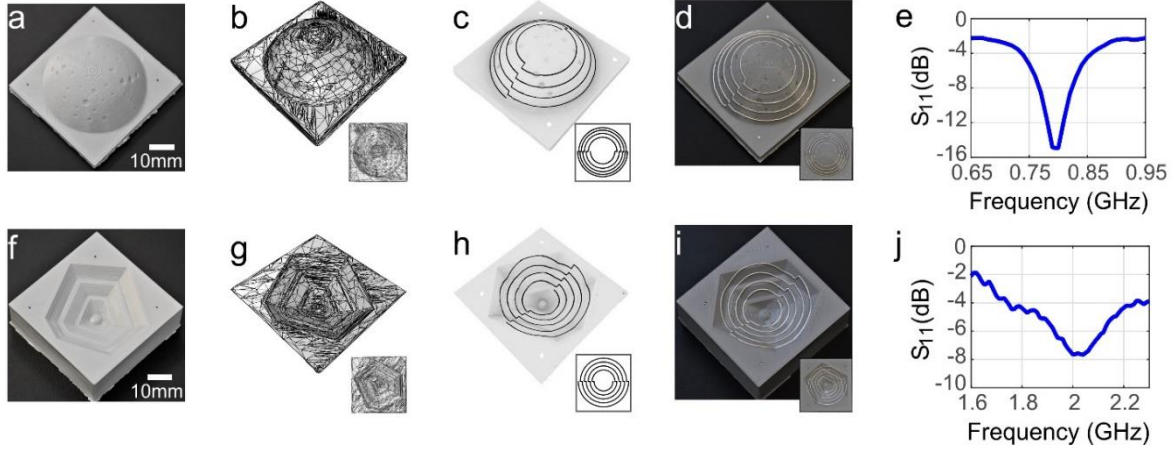


Figure 3.4 Highlight of conformal antenna printing using the PCPP algorithm on 3D structures with complex geometry. Photograph (a) and associated scanning data (b) of the substrate. (c) Rendered projected tool path data onto point cloud data. Photograph (d) and S_{11} response (e) of a 3D-printed conformal spiral antenna on a dimpled hemispherical substrate. Photograph (f) and associated scanning data (g) of the substrate. (h) Rendered projected tool path data onto point cloud data. Photograph (i) and S_{11} response (j) of a 3D-printed conformal spiral antenna on a 3D polyhedral substrate. Point cloud data was decimated for purposes of illustration. Scale bars = 10 mm.

3.3.4 Conformal Antenna 3D Printing on Non-planar Wrinkled and Folded Kapton Films

We first validated the non-planar tool paths to be used for conformal antenna printing by conformal 3D printing of Pluronic F127 hydrogel on randomly wrinkled Kapton film. Pluronic F127 hydrogels were selected to mimic the rheological properties (particularly the yield stress of the conductive epoxy used for antenna fabrication). A photograph and associated point cloud representation of a randomly wrinkled Kapton film are shown in Figures 3.5a and b, respectively. The right panel of Figure 3.5b shows the non-planar tool path associated with a projected spiral

coil antenna. The change in z-axis direction of the tool path (*i.e.*, the height of the printed antenna) was 13.7 mm, the maximum angle of inclination was 79.9°, and the minimum radius of curvature, R , was 0.39 mm. As shown in Figures 3.5c and d, the process enabled conformal microextrusion 3D printing of Pluronic F127 hydrogel on the randomly wrinkled Kapton film.

Having established the capability for conformal 3D printing of curved paths across randomly wrinkled Kapton films, we next examined the ability to deposit material on folded Kapton films that exhibited discontinuities in the slope (see Fig. 5e). As shown in Figures 3.5f – h, the reverse engineering (3D scanning)-driven non-planar path planning approach also enabled conformal 3D printing of spiral paths across folded Kapton films that exhibited topographical features associated with slope discontinuities (*i.e.*, sharp grooves and peaks) (Figure 3.5f). The tool path had a change in z-axis direction of 10.4 mm, maximum angle of inclination of 43.5°, and minimum radius of curvature, R , of 0.28 mm. Photographs of the printed path are shown in Figures 3.5g and h. These data demonstrated that the proposed methodology could achieve conformal 3D printing of a test material across Kapton films with variable 3D topography.

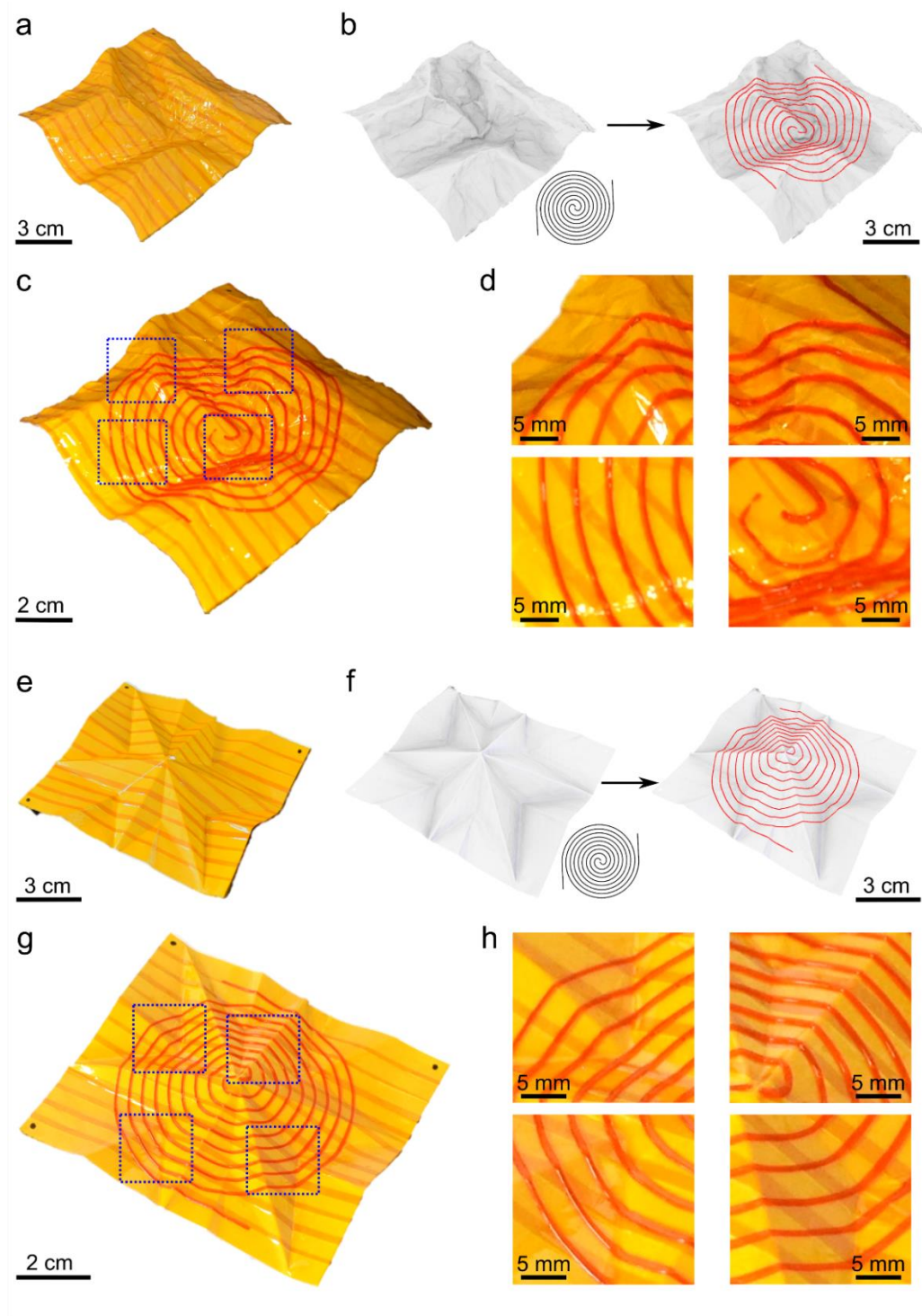


Figure 3.5 Path planning validation for conformal antenna 3D printing on the Kapton films of random 3D topographies (wrinkled and folded). **a)** A photograph of a randomly wrinkled Kapton

film. **b)** Point cloud representation of the film topography and the associated non-planar tool path. **c)** Photograph of the 3D-printed non-planar tool path using Pluronic F127 hydrogel (red dye) on the wrinkled Kapton film with zoomed views **(d)**. **e)** Photograph of a star-like folded Kapton film. **f)** Point cloud representation of the film topography and the associated non-planar tool path. **g)** Photograph of the 3D-printed non-planar tool path using Pluronic F127 hydrogel (red dye) on the folded star-like Kapton film with zoomed views **(h)**.

As shown in Figure 3.6, a Hilbert-curve loop antenna (Figures 3.6a-c) and a triangular monopole antenna (Figures 3.6d-f) were design and printed on curved and folded Kapton films, respectively. The change in z-axis direction of the tool path was 6.35 and 14.4 mm, the maximum angle of inclination was 33.1 and 41.1°, and the minimum radius of curvature, R , was 0.08 and 0.04 mm for the folded and curved antenna, respectively. The antenna designs were selected based on their previous use in multiband flexible antenna applications on planar substrates [153,172]. The S_{11} frequency responses for each antenna are presented in Figures 3.6c and f. The Hilbert-curve loop antenna exhibited resonance at 1.39 and 2.45 GHz with S_{11} less than -10 dB (see Figure 3.6c), while the monopole antenna exhibited resonance at 0.84 and 1.28 GHz with S_{11} less than -10 dB (see Figure 3.6f). The measured resonant frequencies agree reasonably with previously reported values [153,172].

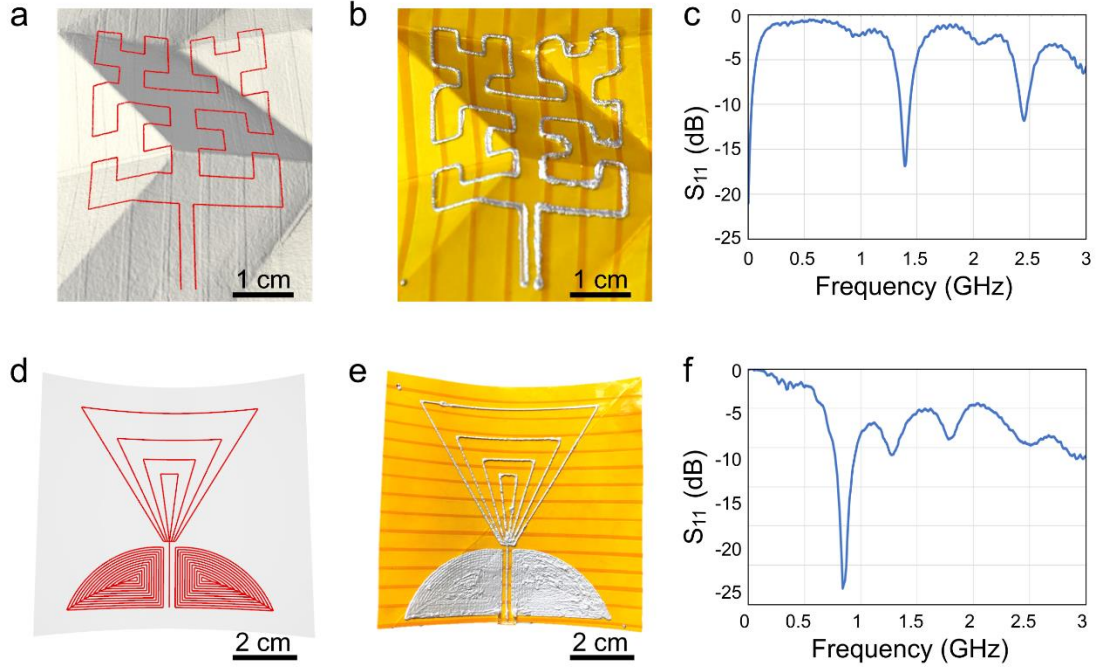


Figure 3.6 3D-printed conformal antennas and frequency response on non-planar Kapton films. **a)** Digital model of a conformal Hilbert-curve loop antenna on a folded Kapton film. **b)** Photograph of a printed Hilbert-curve loop antenna and corresponding S_{11} frequency response **(c)** on a folded Kapton film. **d)** Digital model of a conformal triangular monopole antenna on a concave Kapton film. **e)** Photograph of the printed triangular monopolar antenna and corresponding S_{11} frequency response **(f)** on a concave Kapton film.

3.3.5 Conformal Antenna 3D Printing on Kapton Origami

In order to further demonstrate the versatility of the approach for conformal antenna printing on non-planar films and textiles that exhibit complex geometry, we next examined the integration of conformal antennas with Kapton origami. Electronics integration with origami structures has led to novel technologies, including a non-invasive remote-controlled miniature robot for patching stomach wounds [173], a foldable three-degrees-of-freedom force-feedback

robot for human-robot interaction [174], and a hexagonal bellow-shaped structure that exhibits peristaltic locomotion [175]. Figure 3.7a shows a photograph of a Kapton origami crane that served as a non-planar substrate for conformal 3D printing. The point cloud and 2D tool path associated with a modified Hilbert-curve loop antenna as well as the resultant conformal tool path are shown in Figures 3.7b and c, respectively. The tool path had a change in z-axis direction of 6.1 mm, maximum angle of inclination of 32.2° , and minimum radius of curvature, R , of 0.06 mm. Inspection of the 3D-printed path (see Figures 3.7d and e) suggests that the approach provided quality conformal 3D printing of conductive epoxy on the Kapton origami. The conformal antennas were designed to be $50\ \Omega$ nominal, which provided the reference impedance for the S_{11} measurement. As shown by the S_{11} frequency response in Figure 3.7f, the conformal modified Hilbert-curve loop antenna on the Kapton crane origami wing exhibited a resonant frequency of 1.59 and 2.71 GHz with S_{11} less than -10 dB.

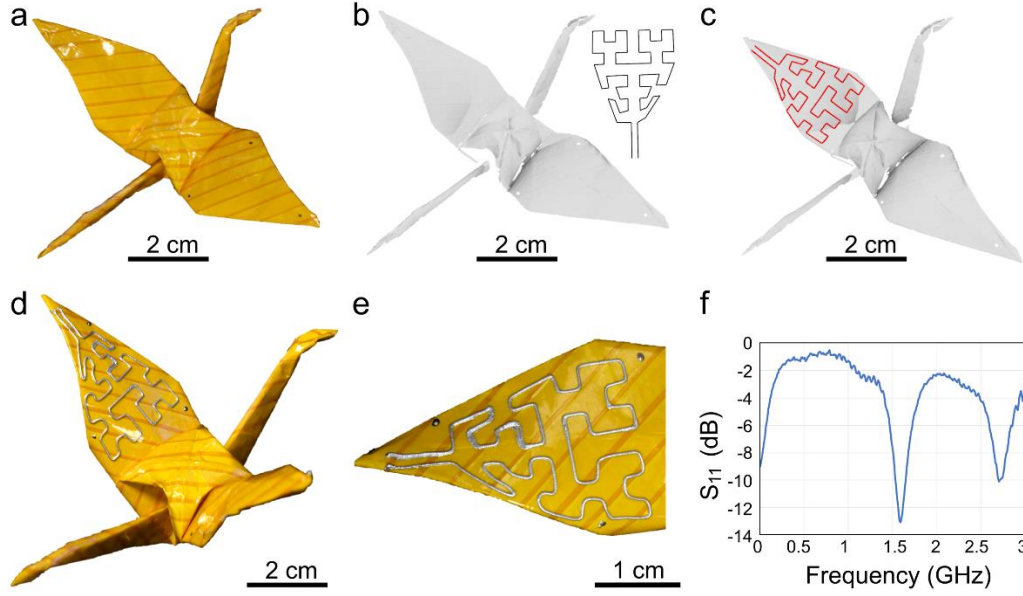


Figure 3.7 Conformal antenna on Kapton-based origami crane. **a)** A photograph of the Kapton-based origami crane substrate. **b)** Reverse engineered digital model of the origami crane with modified loop antenna design. **c)** Highlight the conformal programmed toolpath based on the reverse-engineered model. **d)** A photograph of the 3D-printed conformal antenna on the wing of a Kapton origami crane with a zoomed view **(e)**. **f)** S_{11} frequency response of the conformal printed antenna.

3.4 Discussion

The objective of this work was to create a reverse engineering-driven approach for conformal microextrusion 3D printing capable of printing on one-of-a-kind substrates that lack pre-existing CAD representations of part geometry. Our goal was also to understand the origin of commonly observed defects in conformal microextrusion 3D printing using orthogonal three-axis robots, including tool-surface contact and filament distortion. This method would synergize with applications that involve one-of-a-kind substrates that lack CAD representations, a common

situation in electronic textile manufacturing, among other areas. In this work, we first systematically identified defects associated with path planning without and with corrections for tool geometry, tool trajectory, and object slope (details of which are presented in Supporting Figures S3.2 and S3.3). This provided insight to the origin of high quality obtained using the PCPP algorithm, which contains corrections for tool geometry, tool trajectory, and object topographical features (*i.e.*, the slope and curvature).

One important application of conformal 3D printing is the fabrication of 3D electronics, including three-dimensional sensors and antennas [145,176,177]. In Figures 3.4-3.7, we show that the PCPP algorithm enables the fabrication of novel conformal antennas on various non-planar substrates. It is difficult to conform flexible electronics on rugged uneven surfaces, curved surfaces with sharp edges such as polyhedron surfaces, and non-developable surfaces, such as spheres [145]. For the applications on spherical surfaces, increased area coverage and reduced radius of curvature are determined to be more challenging [145,178]. Therefore, an asymmetrical polyhedron surface with a convex spherical cap and a spherical surface with varying size dimples was designed (see Figure 3.4) and fabricated as substrates for conformal antenna fabrication. The polyhedron surface had sides ranging from 0.85 mm to 33 mm and a spherical cap with R of 3.3 mm. The hemispherical surface ($R = 27\text{mm}$) exhibited dimples with R ranging from 1 to 3 mm.

Here, we utilized a path planning approach based on point cloud data. Thus, while the approach is capable of precision conformal additive manufacturing it requires the substrate to not exhibit changes in position throughout the process that exceed the length scale of the nozzle (*e.g.*, the nozzle diameter). Recently, there has been growing interest in real-time control of the process parameters by incorporating in-situ sensor and cameras into the AM processes [15,179–181]. In

addition to the quality control, computer vision systems and image processing techniques have been used for adaptive path planning for 3D printing [74,75]. For example, Zhu *et al.* has demonstrated an adaptive 3D printing method to fabricate sensors on moving human hands using computer-vision-based tracking techniques [74]. Later, Zhu *et al.* have 3D printed a hydrogel-based sensor on a deforming porcine lung by combining offline machine learning technique with online computer-vision based control [75]. Thus, the PCPP approach presented here could also be integrated with sensors for real-time position monitoring to further extend conformal microextrusion printing capabilities to moving objects.

3.5 Conclusions

Here, we provided a novel reverse engineering-driven methodology for conformal microextrusion 3D printing based on the point cloud representation of substrate geometry. A point cloud-based path planning (PCPP) algorithm enabled conformal 3D printing on one-of-a-kind objects with complex geometry and films of complex topography using user-defined 2D paths of comparable length to the object's radius of curvature (R). New insights into the relationship among nozzle standoff distance, surface topographical features, and 3D printing quality were provided in terms of commonly observed filament flattening and floating defects as well as tool-surface contact defects. Our study also potentially opens the door to the creation of novel conformal antennas, wearable and 3D electronics, electronic textiles, and high-performance electronic films. Future iterations of the PCPP algorithm will include path corrections based on the rheological properties of the deposited material and real-time object and tool position sensing data.

3.6 Supporting Information

These supplementary materials contain: 1) test part design ; 2) results of conformal 3D printing quality with vertical and slope-corrected tool offsets; and 3) non-planar path planning results associated with antenna 3D printing on planar Kapton film. We also include pseudo-codes associated with path planning algorithms. The pseudo-code used for computational characterization of conformal printing quality is also included. This supporting information also includes examples of $\mathbf{S}^r$ and $\mathbf{P}$ (Table S3.1).

3.6.1 Test Part Design

As shown in Figures S3.1k and l, the test part consisted of three regions. The first region of the test part, referred to hereinafter as Region 1, exhibited transitions between ascending and descending features with both constant and non-constant slope (*i.e.*, zero and non-zero curvature, respectively). The transitions were separated by 1 - 5 mm, which was approximately $1.6d - 8.3d$. This design established discontinuities in the slope (*i.e.*, abrupt changes in the direction of a constant surface normal vector). It also established ascending and descending regions of constant slope (*i.e.*, $R = \infty$) that have been previously utilized for conformal microextrusion 3D printing algorithm development [29]. Region 1 also exhibited small cavities with a radius of curvature (R) that ranged from 240 to 820 μm ($\approx 0.4d - 1.4d$). Region 2 demonstrated a similar range of ascending and descending non-planar topographical features that examined a relatively larger range of R from 1 - 5 mm in which slope discontinuities were absent. The features were separated by 2 - 10 mm, which was approximately $3.2d - 16.6d$. Region 2 also contained a topographical feature that exhibited a transition from a finite to an infinite value of R (*i.e.*, a transition from a curved to flat surface of a non-zero slope). Region 3 displayed a similar range of ascending and

descending non-planar topographical features but of a relatively larger value of R and feature separation distance (10 mm). Region 3 exhibited topographical features of relatively larger slopes similar to Region 2, in which slope discontinuities were absent. A photograph of the 3D-printed test part is shown in Figure S3.1m.

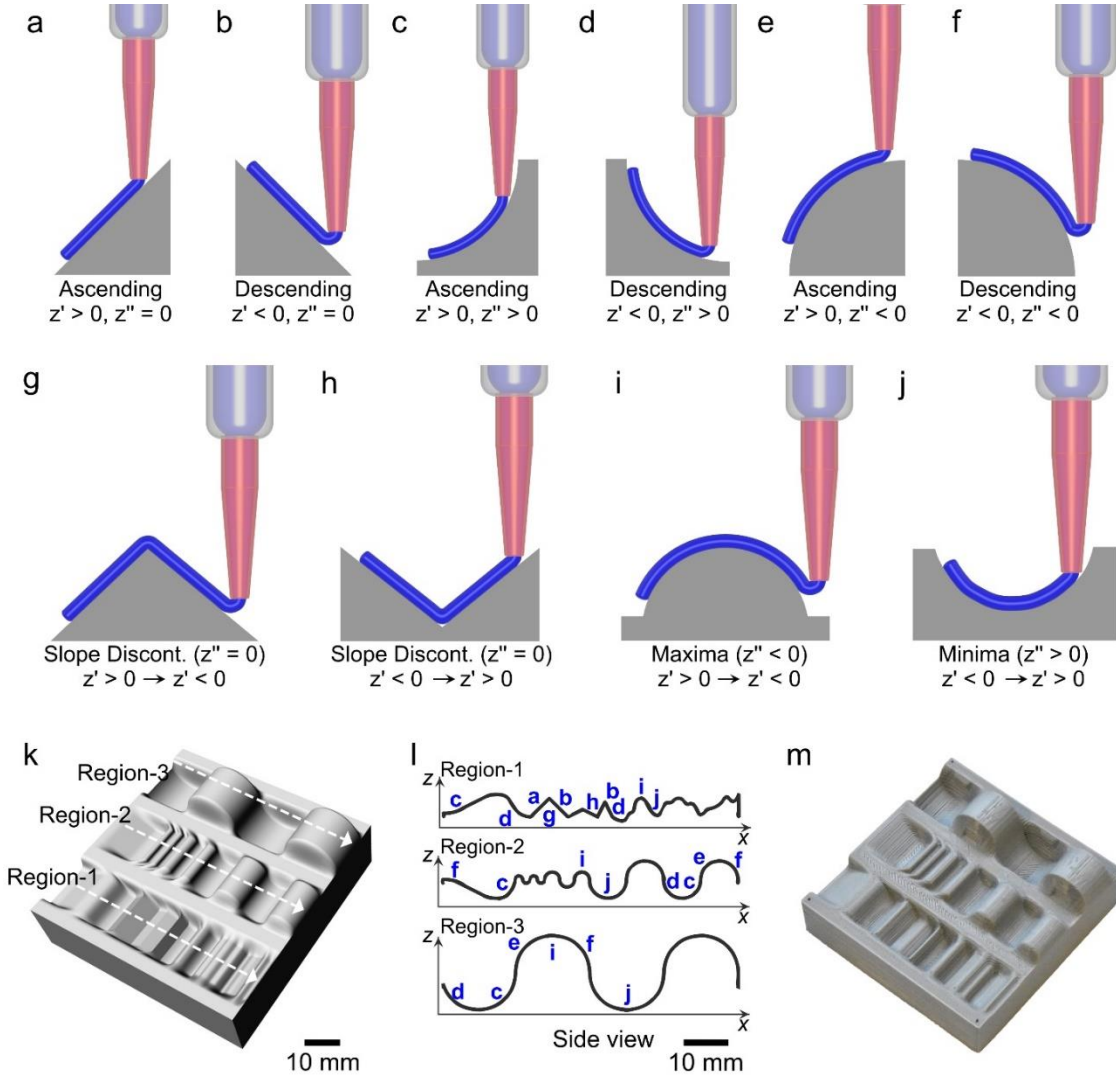


Figure S3.1 Description of various non-planar tool trajectories encountered in conformal 3D printing (a – j). **k)** CAD model of a custom test part fabricated for non-planar path planning

algorithm validation. **l)** Spatial distribution of non-planar tool trajectories across the test part. **m)** Photograph of the test part used for algorithm validation. Scale bars, 10 mm.

Table S3.1: Examples of the matrices associated with $\mathbf{S}^r$ and $\mathbf{P}$ corresponding to the study discussed in Figure 3.2.

$$\mathbf{S}^r = \begin{bmatrix} -58.4037 & -88.5714 & -57.0373 \\ 86.5977 & 153.855 & 153.469 \\ -39.1942 & -53.3039 & -124.727 \end{bmatrix}$$

$$\mathbf{P} = \begin{bmatrix} 88.1799 & 13.4989 & 10.1549 \\ 14.0904 & 11.1944 & 89.0994 \\ -50.7744 & -50.7974 & -50.7314 \end{bmatrix}$$

3.6.2 Conformal Microextrusion 3D Printing Quality in the Absence of Tool Trajectory and Object Geometry Corrections

The PCPP algorithm utilizes the tool geometry, tool trajectory, and point cloud-defined object topographical features, including object slope and curvature, to modify the vertical and lateral positions of each coordinate in the zero-offset conformal tool path $\mathbf{T}^a$. To understand the effect of each characteristic on the print quality, the conformal 3D printing quality was systematically examined in the absence of tool trajectory and object geometry corrections using two simplified versions of the PCPP algorithm: 1) a PCPP algorithm that involves no path corrections for tool trajectory or object topography, and 2) a PCPP algorithm that involves corrections for tool trajectory and object slope, but no path corrections for object curvature. The pseudo-code associated with these algorithms are provided in Algorithm 2 and 3 at the end of this

section. The schematics of the corresponding nozzle standoff distances are shown in Figures S3.2a and b, and Figures S3.3a and b.

3.6.3 *Description of Printing Quality in the Absence of Tool Trajectory and Object Geometry Corrections (Constant Vertical Offset)*

In the absence of path corrections for tool trajectory and object geometry, a simple path correction may only consider the tool geometry as:

$$T_{i_z}^{a*} = T_{i_z}^a + d \quad (\text{S1})$$

where $T_{i_z}^{a*}$ and $T_{i_z}^a$ are the z-coordinates of the offset tool path and the zero-standoff tool path in the 3D printing reference frame. A description of the path planning strategy associated with constant vertical tool shift that neglects the tool trajectory and object geometry is shown in Figure S3.2a. As shown in Figure S3.2b, conformal 3D printing in the absence of tool trajectory and object geometry correction resulted in a non-planar tool path that exhibited an identical profile to the object's surface profile $\mathbf{T}^a$. Thus, the initially projected user-defined tool path (*i.e.*, object topography) and the offset tool path exhibited identical local surface normal vectors and curvatures. The tool path $\mathbf{T}^{a*}$ in Figure S3.2b corresponds to a 2-mm diameter nozzle ($d = 2\text{mm}$).

As shown in Figure S3.2c, in the absence of tool trajectory and object geometry correction, the PCPP algorithm enabled conformal microextrusion 3D printing across each of the regions. However, the absence of tool trajectory and object geometry correction resulted in two 3D printing defects, locations where the 3D-printed filament's thickness and width deviate from the expected value (d), which we refer to as a flattening defect (see Figure S3.2d), and tool-surface contact

(Figure S3.2e). The data in Figures S3.2b-e suggest that the defect locations are dependent on the tool trajectory and object topographical features.

The tool path data T^a and scanning data S^a profiles (see Figure S3.2b) enabled calculation of an expected filament thickness for the path planning approach, defined as the difference between the nozzle diameter (ideal filament thickness) and the expected filament thickness. As shown in Figure S3.2f, the error in the expected filament thickness was dependent on the shape characteristics of the test part, specifically, the slope and curvature. Figure S3.2d shows the dependence of the error in the expected filament thickness on the slope and curvature object. The results indicated that the error was the largest when the slope was negative (*i.e.*, the tool was moving downward). Thus, we found that downward trajectories on concave-up surfaces resulted in negative errors (*i.e.*, flattening defects). As shown in Figure S3.2f, flattening defects increased the width of the printed trace by as much as a factor of two larger than the expected value. The data in Figure S3.2 also show a direct correlation between the absolute value of the error and the slope of the surface. While flattening defects may adversely affect quality in some applications, the flattening artifact could be used as an approach for improving the adhesion of printed material.

In addition to the flattening artifact, conformal 3D printing in the absence of tool trajectory and object geometry correction resulted in a tool-surface contact defect at the peaks of the increasing concave up or decreasing concave down regions and sharp edges. At these locations, the slope of the tool path increased or decreased suddenly, which caused the nozzle to make contact with the surface. In addition to contacting the object, the tool-surface contact defect resulted in a gap in the deposited material at contact and was followed by material accumulation after the

contact point. Thus, the data in Figures S3.2b-f show that the print quality is dependent on the local geometry of the object.

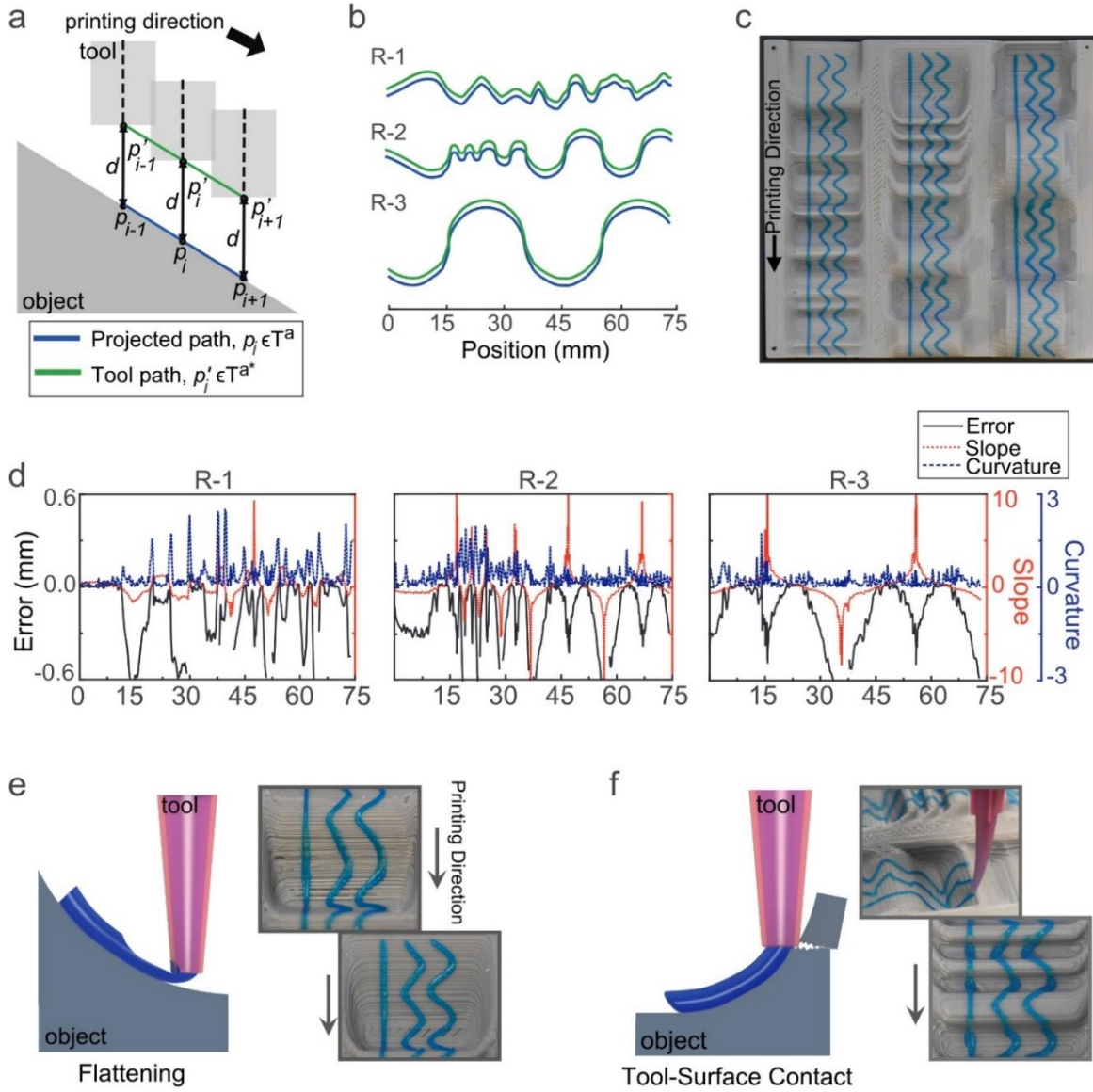


Figure S3.2 a) Illustration of conformal 3D printing quality in the absence of tool trajectory and object geometry correction in which each z-component of the non-planar tool path is offset from the object point cloud z-coordinate by a constant offset d . b) Visualization of the resultant non-planar tool path on the three regions of the test part (an offset distance of $d = 2$ mm was utilized for illustration). c) Photograph of the resultant print quality from a top-down perspective. d)

Computational analysis of non-planar 3D printing quality in terms of the expected filament thickness error versus the local slope and curvature of the object using data shown in panel b. Illustrations and photographs of the observed flattening **(e)** and tool-surface contact **(f)** 3D printing quality defects.

3.6.4 Description of Printing Quality in the Presence of Tool Trajectory and Object Slope Corrections

We next examined the 3D printing quality obtained through the integration of tool trajectory and object slope corrections in the absence of curvature correction. Previous considerations of Vatani *et al.* for slope-based shape corrections of nozzle standoff distance suggest that the distance between the deposition surface and the nozzle tip should depend on the deposition direction and the surface normal vector [9]. In the absence of curvature correction, a path correction that considers tool geometry as well as tool trajectory and object slope can be represented as:

$$T_{ir}^{a*} = T_i^a + d\vec{N}_i + \frac{d_o}{2}\vec{V}_i \quad (\text{S2})$$

where the term $d_o\vec{V}_i/2$ a correction factor for the trajectory that accounts for the 2D tool path direction $\vec{V}_i$ ($\vec{V}_i = [t_{i,x}, t_{i,y}]$) and nozzle outer diameter d_o , and $d\vec{N}_i$ a correction factor for the slope of the surface where $\vec{N}_i$ the normal vector. Unlike the quality obtained in the absence of tool trajectory and object geometry correction, the trajectory and slope corrections offset the x-, y- and z-coordinates of the path by a distance that depends on the nozzle inner and outer diameters as shown in Figure S3.3a. The calculated point represented the left corner of the nozzle when the tool moves in the right direction and vice versa. This point is referred to as the nozzle reference

point T_{ir}^{a*} (see Figure S3.3a). The tool path, $\mathbf{T}^{a*}$, which represents the nozzle center points, was then calculated by adding the outer nozzle radius to the nozzle reference points in the two-dimensional printing direction $\mathbf{V}_i$, which was determined by using x and y axes values of the tangent vector $\mathbf{T}_i$. Thus, trajectory and slope corrections led to a non-planar path that was relatively further away from the surface during downward motion as a result of using a normal vector offset followed by a lateral offset for each path point. While the absence of tool trajectory and object geometry correction led to a non-planar tool path $\mathbf{T}^{a*}$ that exhibited the same length, surface normal vectors, and curvatures as the object profile (*i.e.*, $\mathbf{T}^a$), the trajectory and slope corrections established a different tool path profile that mitigated some of the aforementioned defects.

We note that the tool path $\mathbf{T}^{a*}$ in Figure S3.3b was the output tool path for $d = 2\text{mm}$ which was used to enlarge the difference for visual purposes. As shown in Figures S3.3c-d, the introduction of trajectory and slope corrections reduced the extent of flattening defects relative to that observed in the absence of tool trajectory and object geometry corrections. However, the floating artifacts and tool-surface contact defects were still observed.

The tool-surface contact defect was observed during tool paths with upward trajectories. Downward trajectories on concave-down surfaces resulted in poor material adhesion to the surface, which we refer to as a floating defect (see Figure S3.3e). The floating defect is characterized by a positive error in filament thickness calculations (Figure S3.3d). Floating artifacts were observed at locations that exhibited a negative slope and a decreasing magnitude of curvature relative to the previous location. This defect was mainly observed at surface inflection points as shown in Figures S3.3c-e. In some cases, the material was deposited but in a path that deviated from the defined tool. For example, deviation in the printed filament path by $4d$ was observed at the inflection point

of the path in Region 3 of the test part. In the other cases, the defect led to a discontinuous filament and gap in deposited material (see Region 2).

While the path corrections for tool trajectory and object slope reduced the extent of the flattening defect, the approach is based on a ‘nozzle reference point,’ defined as the closest point to the surface when the tool moves in a downward direction. Thus, the approach neglects the gap between the nozzle and the surface in the z-axis, which may cause the floating defect. For upward trajectories, the nozzle reference point was the furthestmost point from the surface (see Figure S3.3a). As a result, the approach also neglects consideration of the horizontal distance between the nozzle and the surface, which may cause the tool-surface contact defect.

Similar to the results obtained in the absence of tool trajectory and object geometry correction, the error increased at locations where the slope exhibited a positive sign and relatively large absolute value (*i.e.*, ascending paths with large slopes) (Figure S3.3d). However, the inclusion of path corrections for tool trajectory and object slope reduced the error at the regions with the slope of high negative values, which resulted in decreased flattening artifacts. Although path corrections for tool trajectory and object slope minimized the flattening artifacts, which here was observed only when the tool moved through a descending path (*i.e.*, in a downward direction), they did not completely mitigate the floating and tool-surface contact defects. Inspection of Figure S3.3d also shows a correlation between the locations of print quality and defects and the surface curvature.

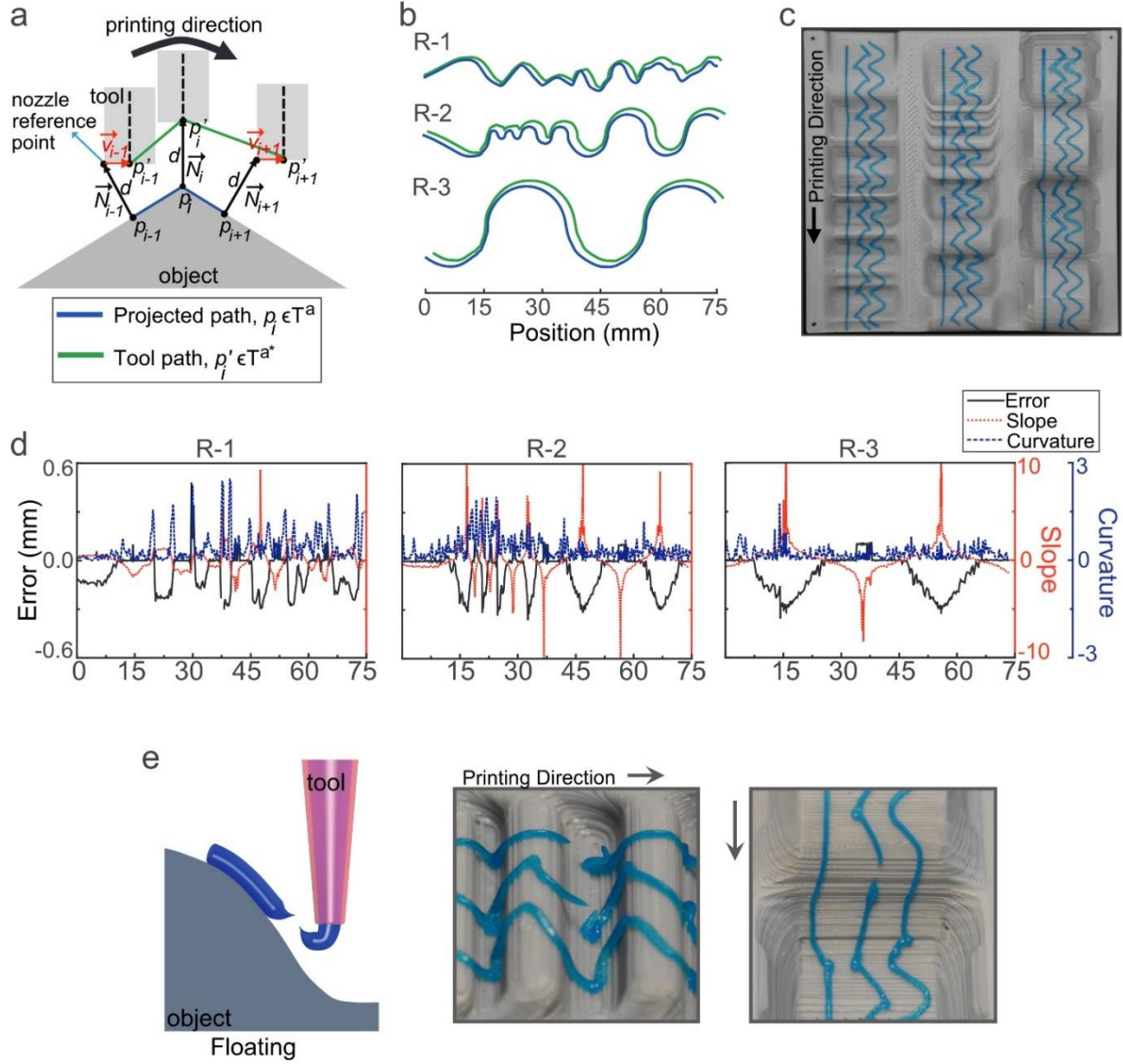


Figure S3.3 **a)** Illustration of the point cloud-based tool path planning algorithm with path corrections for tool geometry, tool trajectory, and object slope. **b)** Visualization of the resultant non-planar tool path on the three regions of the test part (an offset distance of $d = 2$ mm was utilized for illustration). **c)** Photograph of the resultant print quality from a top-down perspective. **d)** Computational analysis of non-planar 3D printing quality in terms of the error in predicted filament thickness versus the local slope and curvature of the object. **e)** Illustrations and photographs of the filament floating (gap) defect that result from the non-planar path planning algorithm.

Algorithm 1 - Registration Algorithm: Tool path alignment-projection algorithm.

Input: $\mathbf{S}$: The mesh structure of the point cloud data that is achieved by the 3D scanner
 $[\mathbf{S}^r]_{3,3}$: Three reference points that are area centroids of the holes in the point cloud data
 $[\mathbf{P}]_{3,3}$: Three reference points that are obtained by the printer controller
 $[\mathbf{T}^{2D}]_{3,m}$: A list of sampled points on the i^{th} 2D path, $T^{2D}_{3,j} = 0$ for all $j = 0, \dots, m$ where $m = \lfloor L_p / 2d \rfloor$
Output: $[\mathbf{T}^a]_{3,m}$: Aligned and projected path points
Initialize $\mathbf{S}^a$, $[\mathbf{T}]_{3,m}$, $[\mathbf{T}^a]_{3,m}$, $\mathbf{G}$;
 $\mathbf{T} \leftarrow$ Project $\mathbf{T}^{2D}$ onto $\mathbf{S}$ in z-axis direction;
Find transformation matrix $\mathbf{G}(\mathbf{S}^r, \mathbf{P})$;
 $\mathbf{S}^a \leftarrow \mathbf{G}\mathbf{S}$; /*align the point cloud data to the 3D printer frame*/
 $\mathbf{T}^a \leftarrow \mathbf{G}\mathbf{T}$; /*align the path points to the 3D printer frame*/
return $\mathbf{T}^a$

Algorithm 2 - Constant-offset PCPP Algorithm: Establishing a constant vertical offset based on the nozzle diameter.

Input: $[\mathbf{T}^a]_{3,m}$: 3D path points on the surface
 d : the inner nozzle diameter
Output: $[\mathbf{T}^{a*}]_{3,m}$: G-code points that the nozzle will follow
for each column j in $\mathbf{T}^a$ **do** /*for each point on the surface*/
 $T_j^{a*} \leftarrow T_j^a$;
 $T_{j,z}^{a*} \leftarrow T_{j,z}^a + d$; /*add d offset to the point in z-axis direction*/
end for
return $\mathbf{T}^{a*}$;

Algorithm 3 - Slope-corrected PCPP Algorithm: Offsetting the path based on the surface normal vector.

Input: $[\mathbf{T}^a]_{3,m}$: 3D path points on the surface
 d : the inner nozzle diameter
 d_o : the outer nozzle diameter
 $[\mathbf{N}]_{3,m}$: A set of the unit normal vector associated with each point of $\mathbf{T}^a$ on $\mathbf{r}(t)$, the curve fit through $\mathbf{T}^a$
Output: $[\mathbf{T}^{a*}]_{3,m}$: G-code points that the nozzle will follow
Initialize $[\mathbf{V}]_{3,m}$;
for each column j in $\mathbf{T}^a$ **do** /*for each point on the surface*/
 $V_j \leftarrow T_{j+1}^a - T_j^a$;
 $V_{j,z} \leftarrow 0$; /* V is the printing direction in x - and y - axes*/
 $T_j^{a*} \leftarrow T_j^a + dN_j + \frac{d_o}{2} V_j$;
end for
return $\mathbf{T}^{a*}$;

Algorithm 4 - PCPP Algorithm: Offsetting the path based on the local tool-surface location.

Input: $[\mathbf{T}^a]_{3,m}$: 3D path points on the surface
 d : the inner nozzle diameter
 d_o : the outer nozzle diameter
 $[\kappa]_m$: A set of curvature values associated with each row of $\mathbf{T}^a$ on $\mathbf{r}(t)$
 $\mathbf{S}$: The mesh structure of the point cloud data that is achieved by the 3D scanner

Output: $[\mathbf{T}^{a*}]_{3,m}$: G-code points that the nozzle will follow

Initialize $[\mathbf{V}]_{3,m}, L_j, M_j, C, p_j, X$;

for each column j in $\mathbf{T}^a$ **do** /*for each point on the surface*/
 $V_j \leftarrow T_{j+1}^a - T_j^a$;
 $V_{j,z} \leftarrow 0$; /* V is the printing direction in x- and y- axes*/
 $T_j^{a*} \leftarrow T_j^a$;
 $T_{j,z}^{a*} \leftarrow T_{j,z}^a + d$;
 $C_j \leftarrow$ a circular plane surface on T_j^{a*} with diameter of d_o ; /*simulates the nozzle tip*/
if there exists an intersection points list $\{C_j \cap \mathbf{S}\}$ **then**
 $p_j \leftarrow$ the centroid of the list $\{C_j \cap \mathbf{S}\}$;
 $L_j \leftarrow d_o/2 - |T_j^{a*}, p_j| + tol$; /*tol is the tolerance set by the user*/
 $Q \leftarrow \overrightarrow{p_j, T_j^{a*}}$;
 $T_j^{a*} \leftarrow T_j^{a*} + L_j Q$;
if $T_{j,z} < 0$ **then** /*if going downwards*/
if $\kappa_j < 1/d$ **then**
 $M_j \leftarrow 0.5d(1 + d\kappa_j)$;
else
 $M_j \leftarrow d$;
end if
 $T_j^{a*} \leftarrow T_j^{a*} + M_j V_j$;
end if
else if $T_{j,z} < 0$ **then** /*if going downwards but no intersection*/
if there exists an intersection point $\{|T_j^{a*}, T_j^{a*} - dV_j| \cap \mathbf{S}\}$ **then**
 $p_j \leftarrow |T_j^{a*}, T_j^{a*} - dV_j| \cap \mathbf{S}$;
 $M_j \leftarrow \frac{d_o}{2} + M_j - |T_j^{a*}, p_j|$;
 $T_j^{a*} \leftarrow T_j^{a*} + M_j V_j$;
end if
end for
return $\mathbf{T}^{a*}$;

Algorithm 5 - Computational Analysis of filament thickness.

Input: $[\mathbf{T}^a]_{3,m}$: 3D path points on the surface
 $[\mathbf{T}^{a*}]_{3,m}$: G-code points list which is the output of the algorithm analyzed
 d : the inner nozzle diameter
 d_o : the outer nozzle diameter
 $[\mathbf{N}]_{3,m}$: A set of the unit normal vector associated with each point of $\mathbf{T}^a$ on $\mathbf{r}(t)$, the curve fit through $\mathbf{T}^a$
 $[\mathbf{T}]_{3,m}$: A set of the unit tangent vector associated with each row of $\mathbf{T}^a$ on $\mathbf{r}(t)$, the curve fit through $\mathbf{T}^a$
 $\mathbf{S}$: The mesh structure of the point cloud data that is achieved by the 3D scanner

Output: $[D]_m$: The filament thickness at each point in $\mathbf{T}^a$
 $[Flattening]_m$: Boolean matrix indicating if the flattening artifact is observed
 $[Floating]_m$: Boolean matrix indicating if the floating artifact is observed
 $[Contact]_m$: Boolean matrix indicating if the tool-surface contact defect artifact is observed

Initialize $[\mathbf{F}]_{3,m}, [\mathbf{V}]_{3,m}, \mathbf{c}(t)$;

for each column j in $\mathbf{T}^a$ **do** /*for each point on the surface*/
 $C_j \leftarrow$ a circular plane surface on T_j^{a*} with diameter of d_o ; /*simulates the nozzle tip*/
 $V_j \leftarrow T_j$ and $V_{j,z} \leftarrow 0$; /* V is the printing direction in x and y axes*/
if there is an intersection point p_j between $\mathbf{S}$ and C_j **then** /*tool-surface contact defect*/
 $Contact_j \leftarrow 1$;
 $F_j \leftarrow []$;
else
 if $T_{j,z} < 0$ **then** /*if going downwards*/
 $F_j \leftarrow T_j^{a*} - (d_o/2)V_j$;
 else /*if going upwards or straight*/
 $F_j \leftarrow T_j^{a*} + (d/2)V_j$;
 end if
end if
 $\mathbf{c}(t) \leftarrow$ Polycurve fit through F_j ;
 $p_j \leftarrow$ the intersection point between $\mathbf{c}(t)$ and $(T_j^a + 2dN_j)$;
 $D_j \leftarrow |T_j^a, p_j|$;
if $D_j < d - tolerance$ **then** /*flattening artifact*/
 $Flattenning_j \leftarrow 1$;
else if $D_j > d + tolerance$ **then** /*floating artifact*/
 $Floating_j \leftarrow 1$;
end if
end for
return $[D]_m, [Flattening]_m, [Floating]_m, [Contact]_m$;

4 Closed-loop Controlled Conformal Microextrusion Additive Manufacturing on Moving Objects via Real-time Localized Object Position Sensing

The ability to deposit materials on moving substrates and objects is central to various emerging additive manufacturing applications, including *in situ* bioprinting and 3D printing in mobile and extreme environments. Here, we report a novel closed-loop controlled path planning method for planar and non-planar additive manufacturing on moving substrates and objects via real-time sensing of local object-tool offset that requires no description of the object geometry prior to fabrication and no global description of object geometry during processing. Feedback control of the microextrusion nozzle z-axis position via real-time sensing of nozzle-surface offset using 1D laser displacement sensors enabled conformal 3D printing on moving substrates and objects. The utility of the method was demonstrated by microextrusion additive manufacturing on planar substrates oscillating at the frequencies associated with tissue motion caused by human physiological processes, including respiration and the heartbeat. The method enabled conformal microextrusion additive manufacturing in the presence of substrate or object motion, including random vertical displacement (*i.e.*, step changes) and continuous vibration (amplitude (A) = $0.8 - 6.7d$, frequency (f) = 0.2, 0.4 and 1.3 Hz, where d is the nozzle diameter). The method was also validated by conformal microextrusion additive manufacturing on a human hand in the presence of random vertical motion ($A = 0 - 34.5d$). In summary, this work provides an advance in closed-loop path planning for microextrusion additive manufacturing on moving substrates and objects. The created closed-loop path planning methodology and additive manufacturing process may potentially support various emerging additive manufacturing applications, including *in situ*

bioprinting and additive manufacturing in mobile and extreme environments that are prone to mechanical disturbance, such as vehicles, vessels, aircraft, and spacecraft.

4.1 Introduction

State-of-the-art additive manufacturing processes often begin with a combination of reverse engineering (*e.g.*, object imaging) and computer-aided design processes [55–59]. In the majority of applications, the part is first fabricated and subsequently transferred to a substrate or target for use [4,50,51,60]. While such methods have enabled the fabrication of complex parts exhibiting anatomical and personalized geometry [4,54,61–65], relatively fewer studies have addressed the challenges of conformal and *in situ* additive manufacturing on target objects that exhibit complex geometry [182–184], which can potentially mitigate challenges associated with part transfer and integration that may arise in traditional ‘fabricate-and-transfer’ methods. For example, parts may exhibit geometric mismatch with the target following fabrication or the quality of the part may be affected during transfer and integration [5,68,185].

While considerable strides have been made regarding conformal additive manufacturing on stationary objects, there remains a demand for methods that enable both planar and non-planar (*i.e.*, conformal) additive manufacturing on moving substrates and objects. For example, the ability to achieve robotically-directed material assembly on moving substrates has the potential to improve the quality of existing additive manufacturing processes that experience mechanical disturbances, such as associated with process actuators and background facility vibrations. For example, movement of astronauts and payloads in the International Space Station, and motion of the space station during attitude control generate transient vibrations in the medium frequency

category ($10^{-3} - 1$ Hz) [186]. Additive manufacturing on moving substrates and objects can also help support emerging additive manufacturing applications associated with part surface property modification, integration of functionality [183], and repair (*e.g.*, *in situ* bioprinting) [5,68,182,185,187–190]. Further, the ability to robotically deposit and assemble material on moving substrates and objects can potentially improve the quality of additive manufacturing applications in mobile and extreme environments, such as vessels, vehicles, aircraft, and spacecraft. While various non-planar path planning methods now enable robotically-directed material deposition and assembly on complex structures [183,184,190], the path planning methods were primarily open-loop and required a digital description of the substrate or object geometry in the form of CAD or imaging data. In addition, they were typically only applicable for additive manufacturing on stationary substrates and objects.

Based on the motivation to improve the quality and scalability of existing additive manufacturing processes as well as to establish novel additive manufacturing applications, various studies have reported advances in integrated online process monitoring and control [15,16,191,192], including mechanical disturbances and substrate-object motion during fabrication [74,75,192]. A number of studies have established the feasibility and motivation for additive manufacturing on moving substrates and objects, such as for *in situ* bioprinting, integration of functionality, and sensor fabrication applications. For example, Armstrong *et al.* integrated a laser displacement sensor into a bioprinting system to control the reference machine path to improve the spatial material extrusion for the next print iteration [8,72]. O'Neill *et al.* attempted to ink-jet print hydrogels onto unconstrained human hand using a commercial hand tracking system and a depth sensing profilometer [73]. Zhu *et al.* demonstrated an adaptive

extrusion-based 3D printing method to fabricate sensors on moving human hands using computer-vision and image-processing techniques [74]. More recently, Zhu *et al.* 3D printed a hydrogel-based sensor on a deforming porcine lung by combining offline machine learning methods and online computer-vision based control [75]. While these studies established the feasibility for *in situ* additive manufacturing on moving objects, they were primarily based on process monitoring strategies that generate high-dimensional sensor data (*e.g.*, image data) that describes global object geometry or position characteristics in real-time.

Here, we provide a novel closed-loop controlled path planning method for planar and non-planar additive manufacturing on moving substrates and objects via real-time sensing of local object-tool offset that requires no *a priori* description of the substrate or object geometry and no global description of object geometry during processing. We first identify thresholds in object movement that may be tolerated by the established non-planar path planning method in Chapter 3 [183] that is among the current state of the art for conformal additive manufacturing in the absence of CAD data. We then report a novel closed-loop tool path planning method for real-time control of the microextrusion nozzle z-axis position based on localized monitoring of the nozzle-surface offset (*i.e.*, separation distance) from a process-integrated 1D laser displacement sensor. The ability to mitigate mechanical disturbances during microextrusion additive manufacturing on planar substrates and non-planar objects was demonstrated by studies on oscillating substrates with frequencies associated with various physiological processes (*e.g.*, human respiration and heart rates) and fabrication of multi-layer constructs on objects of complex geometric and organic shape, respectively. The utility of the method was also demonstrated by conformal additive

manufacturing of multi-layer 3D constructs on a moving human hand undergoing random vertical displacement greater than one order of magnitude larger than the nozzle diameter (d).

4.2 Materials and Methods

4.2.1 Materials

Polylactic acid (PLA) filament was purchased from LulzBot. Cellulose nanofibrils were from the University of Maine Process Development Center (PDC) (Orono, ME). Ultrapure deionized water (DIW) was from a commercially-available DIW system (Direct-Q 3UV; Millipore). Microbially-produced hyaluronic acid (60 kDa) was from LifeCore (Chaska, MN, USA). Pluronic F-127 (PF127), dichloromethane (DCM), 4-nitrophenyl chloroformate, sodium sulfate, sodium chloride, diethyl ether, phosphate-buffered saline (PBS), 1-ethyl-3-(3-dimethylaminopropyl)-carbodiimide (EDC), dopamine hydrochloride, 2-(N-morpholino) ethanesulfonic acid (MES), gelatin (50-100 kDa, from porcine skin, 300 g bloom) and N-hydroxysuccinimide (NHS) were from MilliporeSigma. Hydrochloric acid (12M; HCl) was from ThermoFisher.

4.2.2 Design and Fabrication of Test Parts

The substrates used in the study were created using a computer-aided design (CAD) software (Rhinoceros 3D) and were fabricated using a plastic extrusion 3D printer (Mini2; LulzBot) and PLA. All test parts were printed using vendor recommended settings. Briefly, a linear velocity of 60 mm/s, layer spacing of 0.18 mm, and gradual infill density ranging from 10% to 90% were used to fabricate the test parts.

4.2.3 Hydrogel Preparation

Pluronic F-127 hydrogel (30 wt.%) containing 10 wt.% cellulose nanofibrils served as the test material for 3D printing. Prior to the use, the ink was mixed for three minutes (ARE-310; Thinky) to ensure the dispersion of the cellulose nanofibrils and the coloring agent. A gelatin- and hyaluronic-conjugated Pluronic F127 hydrogel was prepared as described in the previous study [193].

4.2.4 3D Scanning for Open-Loop Point Cloud-based Path Planning Algorithm

Prior to 3D scanning, three user-defined reference points (~1 mm diameter) were placed around the perimeter of the object using a black marker to provide reference points for the 3D printing frame. The object was then scanned using a calibrated single camera-projector structured-light scanning system (HP 3D Structured Light Scanner Pro S2; HP) to acquire the point cloud data following our previously reported protocols [47,49,167,168,183]. Briefly, the point cloud data was converted into a triangulated mesh file using the vendor-provided software, which provided one of three inputs to the PCPP algorithm (the other two inputs being the reference points for the 3D printing reference frame and the user-defined planar tool path).

4.2.5 Conformal In Situ Bioprinting on Porcine Brain Cortex using Point cloud-driven Path Planning

Fresh, adult porcine brains ($n = 3$) for *in situ* bioprinting studies were procured from a local abattoir. The brains were procured by first removing the head *en bloc*. Subsequently, the brain was exposed by removing a region of the skull (~ 60 cm²) using three sloped manual cuts with a hand saw (24 TPI) (see Supporting Figure S4.1). Following the removal of the skull, the meninges was removed to expose the cortex. Tissues were utilized within 2 hours of procurement. Following

removal of the skull and meninges, the geometry of the brain was acquired by 3D scanning. A circular filled path (13.5 - 16.5 mm diameter ellipse; 644 mm; 6762 points) served as the input planar path for *in situ* bioprinting. A gelatin- and hyaluronic-conjugated pluronic F127 hydrogel was conformally printed using a point cloud-based path planning (PCPP) algorithm that was proposed in Chapter 3 [183] across the exposed brain tissue with a 27-gauge tapered tip ($d = 210\ \mu\text{m}$), extrusion pressure of 14.6 psi, and printing speed of 5 mm/s under ambient temperature, which enabled matching between the average material deposition velocity and the printing speed (*i.e.*, feedrate).

4.2.6 Conformal In Situ Bioprinting on the Hand and Face of a Human Subject using Point cloud-driven Path Planning

For *in situ* bioprinting on the hand, the hand geometry was first acquired by 3D scanning. A complex planar path (906 mm; 3016 points) was designed using a NURBS curve with a degree of three based on a single line artwork (<https://www.moganji.com/pictures>). Prior to printing, the hand was Pluronic F127 hydrogel was conformally printed using the PCPP algorithm [183] on the subject's unconstrained hand with a 20-gauge tapered tip ($d = 603\ \mu\text{m}$), extrusion pressure of 12 psi, and printing speed of 5 mm/s. For *in-situ* bioprinting on the nose, the face geometry was first acquired by 3D scanning (eye protection that provided full obstruction of the structured light was also worn throughout the process). A Virginia Tech "VT" logo was designed as the input planar path for *in situ* bioprinting. A single-layer of Pluronic F127 hydrogel was conformally printed using the PCPP algorithm [183] on the unconstrained face of a human with a 16-gauge tapered tip ($d = 1194\ \mu\text{m}$), extrusion pressure of 5.2 psi, and printing speed of 4 mm/s, which enabled matching between the average material deposition velocity and the printing speed. No restraints

were utilized during this study to prevent movement of the subject's hand or face during scanning, generation of tool path data, and 3D printing. The eyes of the human subject were positioned beyond the system range of motion to prevent any contact in the event of motion control system malfunction. The position of the human subject's hand and face was obtained during the conformal 3D printing process using a 1D laser displacement sensor (IL-030; Keyence).

4.2.7 Closed-loop Controlled Tool Path Planning for Microextrusion 3D Printing via Real-time Nozzle-Surface Offset Sensing

The process consisted of a custom microextrusion 3D printing system, which included a digital pressure regulator (Ultimus V; Nordson), a 1D laser displacement sensor (IL-030; Keyence; sampling rate = 1 ms, 16-point moving average), and a three-axis robot (AGS1000 – x, y axes; ATS100 – z-axis; Aerotech). The default servo loop parameters for robot motion control (x-axis: $K_{pos}=28.37$, $K_i=95.21$, $K_p=13740$; y-axis: $K_{pos}=44.56$, $K_i=137.3$, $K_p=12620$; z-axis: $K_{pos}=70.9$, $K_i=2366$, $K_p=136700$, where K_{pos} is the proportional gain of the position loop; K_i and K_p are the integral and proportional gain of the velocity loop, respectively). The closed-loop controlled tool path planning was programmed using motion controller software (A3200; Aerotech). To enable real-time object position sensing, the non-contact 1D laser displacement sensor was mounted adjacent to the extruder (displaced by 0.1 mm in the x-direction). The measurement range of the laser sensor was 20 to 45 mm with a reference distance of 32 mm. The angle of the microextrusion syringe barrel with respect to the z-axis was adjusted to position the nozzle tip 0.1 mm behind the laser spot center. A 20-gauge 0.5-inch long nozzle with a 45° bent tip was used throughout the study.

The distance between the laser spot location and the nozzle center in the x-axis, d_s , was selected to capture the movement of the next tool path point and avoid interference from the extruded material. Throughout this study, $d_s = 0.1 \text{ mm} + r_o$, where r_o is the nozzle outer radius. Thus, the sensor moved with the extrusion tool at a constant speed in each axis (v_x , v_y , and v_z) based on the user-defined planar tool path design ($\mathbf{T}=\{x_n, y_n\}$). The nozzle height was updated continuously based on the position of the object at the laser spot location. The nozzle height (*i.e.*, z-axis position of the robot) was controlled using proportional feedback based on the real-time nozzle-surface offset measured by the 1D displacement sensor. The error (e) was defined as the difference between the reference standoff distance (d) (the setpoint of the nozzle position for optimal printing) and the instantaneous distance between the object and the nozzle at the laser spot location ($d_n(t)$); ($e(t) = d - d_n(t)$). The reference standoff distance was set as d , which is the nozzle diameter, and $d_n(t)$ was given based on the real-time laser displacement sensor voltage output as $d_n(t) = cV(t) - L_0$, where V is the sensor output voltage, c is a user-defined conversion coefficient, and L_0 is a user-defined scaling parameter for nozzle offset calculation ($c = 5 \text{ mm/V}$ and $L_0 = -13 \text{ mm}$ for the sensor used in this study). In Chapter 3, we showed that the optimal nozzle-object separation (*i.e.*, standoff) distance is dependent on features of the object's local geometry (*i.e.*, the slope along the tool path) and the tool trajectory [183]. Therefore, the tool path points were adjusted based on the local slope and tool trajectory to mitigate commonly observed conformal 3D printing defects. The tool path point was shifted in the x-axis direction by r_o to position the back of the nozzle at the measuring point with a reference standoff distance. Similarly, the tool path point was shifted in the negative x-axis direction by r to avoid tool-surface contact by positioning the front of the nozzle at the measuring point with a reference standoff distance. User-defined

paths were discretized to generate motion commands capable of resolving the path. The path density was determined by the metric of six path points per nozzle diameter (d) (i.e., paths contained $n = 6L_x/d$ points, where L_x is the total length of the user-defined path in x-axis). Therefore, the incremental motion command in the z-axis was determined by the interpolation of the desired shift in the z-axis and the distance between two consecutive path points in the x-axis. The motion command in the z-axis, $z_n(t)$, at time t was calculated based on the following three cases determined by the slope between two consecutive measuring points, $m(t)$:

Case1: Downward tool trajectory ($m(t) < -0.2$).

$$z_n(t) = de(t)/6(d_s + r_o) \quad (15)$$

Case2: Upward tool trajectory ($m(t) > 0.2$).

$$z_n(t) = de(t)/6(d_s - r_o) \quad (16)$$

Case3: Near-planar tool trajectory ($-0.2 \leq m(t) \leq 0.2$).

$$z_n(t) = de(t)/6(d_s) \quad (17)$$

where $e(t) = d - d_n(t)$ (Pseudocode is provided in Supporting Table S4.1 under the Section 4.5). This adjustment was only applied to conformal 3D printing on stationary objects and omitted for the applications on moving objects to reduce the reaction time. For conformal 3D printing on moving objects, incremental motion command in z-axis was set as the error ($z_n(t) = e(t)$). The sampling rate for the measured nozzle-surface offset $d_n(t)$ ranged from 45-90 ms and was determined by the time that the incremental motion command was completed in each axis ($\{x_n(t), y_n(t), z_n(t)\}$ divided by the relative axis velocities $\{v_x, v_y, v_z\}$). An additional 1D laser displacement sensor was attached next to the stage at a fixed location pointing to the moving stage to measure the object motion during printing.

4.2.8 *Microextrusion 3D Printing Studies on Stationary Objects*

Single- and multi-layer Pluronic F127 hydrogel constructs were conformally 3D printed on the polyhedral and dimpled-hemisphere test parts that were used in Chapter 3 [183] using a 20-gauge bent metal tip ($d = 603 \mu\text{m}$), extrusion pressure of 22 psi, and printing speed of 2.5 mm/s.

4.2.9 *Microextrusion 3D Printing Studies on Moving Objects*

A manual micromanipulator (World Precision Instruments; Sarasota, FL) was used to vary the position of a planar substrate during printing for analysis of the closed-loop path planning method. Multi-layer triangular constructs ($L_1, L_2, L_3 = 26.87 \text{ mm}, 26.87 \text{ mm}, 38 \text{ mm}$) were printed on an oscillating planar substrate ($25 \times 76 \times 1 \text{ mm}^3$) at frequencies ranging from 0.2 – 1.3 Hz and vibration amplitudes ranging from 0.5 – 4 mm (*i.e.*, $0.8d - 6.7d$). Hydrogel 3D printing was performed using a 20-gauge tapered tip ($d = 603 \mu\text{m}$), extrusion pressure of 23 psi, and printing speed of 10 mm/s in the z-axis and 1 mm/s in the x- and y-axes. For the applications in the presence of substrate vibration, the extrusion nozzle was positioned 5-10 mm away from the substrate/object in the z-axis direction at the start of the tool path in the absence of extrusion to provide an initial condition for the tool position in the machine code. To remove the limitations of path discretization on the motion controller sampling rate, an asynchronous motion command (A3200; Aerotech) was used in the x- and y-axes. The Asynchronous motion command in the motion control software (A3200; Aerotech) enabled the tool path planning program to continue executing the feedback loop and z-axis motion commands without waiting for the movement in the x- and y-axes to be completed (see Supporting Table S4.2 in the Section 4.5).

An unconstrained hand was positioned on the custom spring stage to allow for arbitrary movement in the z-axis but limit movement in x- and y-axis. Pluronic F127 hydrogel multi-layer

triangular constructs and single-layer filled square paths ($10 \times 16 \text{ mm}^2$) were conformally 3D printed on the hand using a 20-gauge tapered tip ($d = 603 \text{ }\mu\text{m}$), extrusion pressure of 27 psi, and printing speed of 20 mm/s in the z-axis and 2.5 mm/s in the x- and y-axes. *Caution:* Safety precautions were undertaken to avoid any potential tissue-machine or -tool contact in the event of unforeseen system malfunction (*e.g.*, stage acceleration toward the human).

4.2.10 Experimental Analysis of Printing Quality

The quality of printed material on the stationary and moving substrates was characterized by image analysis. Photographs of the printed constructs were acquired by using a digital camera (D7200; Nikon) from the top view immediately following the 3D printing process. Each printed construct was analyzed using image analysis software (ImageJ; NIH) and CAD software (Rhinoceros 6). The deposited filament was isolated using the color threshold for blue which was the ink color. Then, the reference filament and the deposited filament were aligned using the coordinate (x- and y- axis) reference points. The area of the deposited filament (A_d) was defined as the surface area of the filament from top view (*i.e.*, filament width $\times$ length). The overlap area (A_i) between the deposited filament and the reference area (A_r) was calculated as $A_i = A_d \cap A_r$ and the overlap ratio (OR) as A_i/A_r . The error was categorized into two types: underbuild and overbuild of the material. Underbuild error was used when the area occupied by the deposited filament is less than the reference area, while overbuild error represented that the area occupied by the deposited filament is larger than the reference. The underbuild area (A_u) was defined as the difference between the reference filament area and the overlap area ($A_u = A_r - A_i$) and overbuild area (A_o) was calculated as the difference between the deposited filament area and the overlap area

($A_o = A_d - A_i$). Thus, the normalized errors for underbuild and overbuild were defined as the underbuild area ratio, $\bar{e}_u = A_u/A_r$, and the overbuild area ratio, $\bar{e}_o = A_o/A_r$, respectively.

4.3 Results and Discussion

4.3.1 Characterization of State-of-the-Art Open-loop Point Cloud-based Path Planning Method Tolerance to Substrate Movement for Motivation and Benchmarking of the Closed-loop Path Planning Method

Various non-planar path planning methods based on CAD or high-dimensional data (*e.g.*, point cloud) are now available for conformal additive manufacturing [182–184]. In Chapter 3, we reported a point cloud-based path planning method for conformal microextrusion additive manufacturing on thin films and folded films of near-arbitrary topography [183]. Albanna *et al.* presented a similar method for *in situ* skin bioprinting applications that generates a planar nozzle path based on the wound topography obtained by 3D scanning [182]. While these methods previously enabled nonplanar and planar microextrusion 3D printing of functional materials, including conducting materials and bioinks, on stationary objects (*e.g.* nonplanar polyimide films [183] and wounds [182]), it was of interest to characterize their tolerance to the object movement during fabrication. Various substrates and tissues were utilized in this study as test objects for algorithm validation. The paths across various objects, including a porcine brain cortex, human hand, and face, and corresponding printing results obtained using a previously developed non-planar path planning method based on high dimensional point cloud, the PCPP method, [183] are shown in Figure 4.1a-f. The associated movement of the object during printing is shown in Figure 4.1g and h. As shown in Figure 4.1a-f, we found that open-loop path planning based on initially obtained point cloud data-enabled 3D printing of filled and complex unfilled paths on the cortex

of a porcine brain and on the unconstrained human hand and face, which exhibit vertical displacements ranging from 0.01 to 0.2 mm (0.3*d*) during fabrication (see Figure 4.1g-h). However, the open-loop method based on 3D scanning did not facilitate quality microextrusion 3D printing in the presence of object displacements greater than 0.2 mm (*i.e.*, 0.3*d*) during fabrication (results of failed prints not shown), which were observed when the participant spoke during printing (see Figure 4.1g-h).

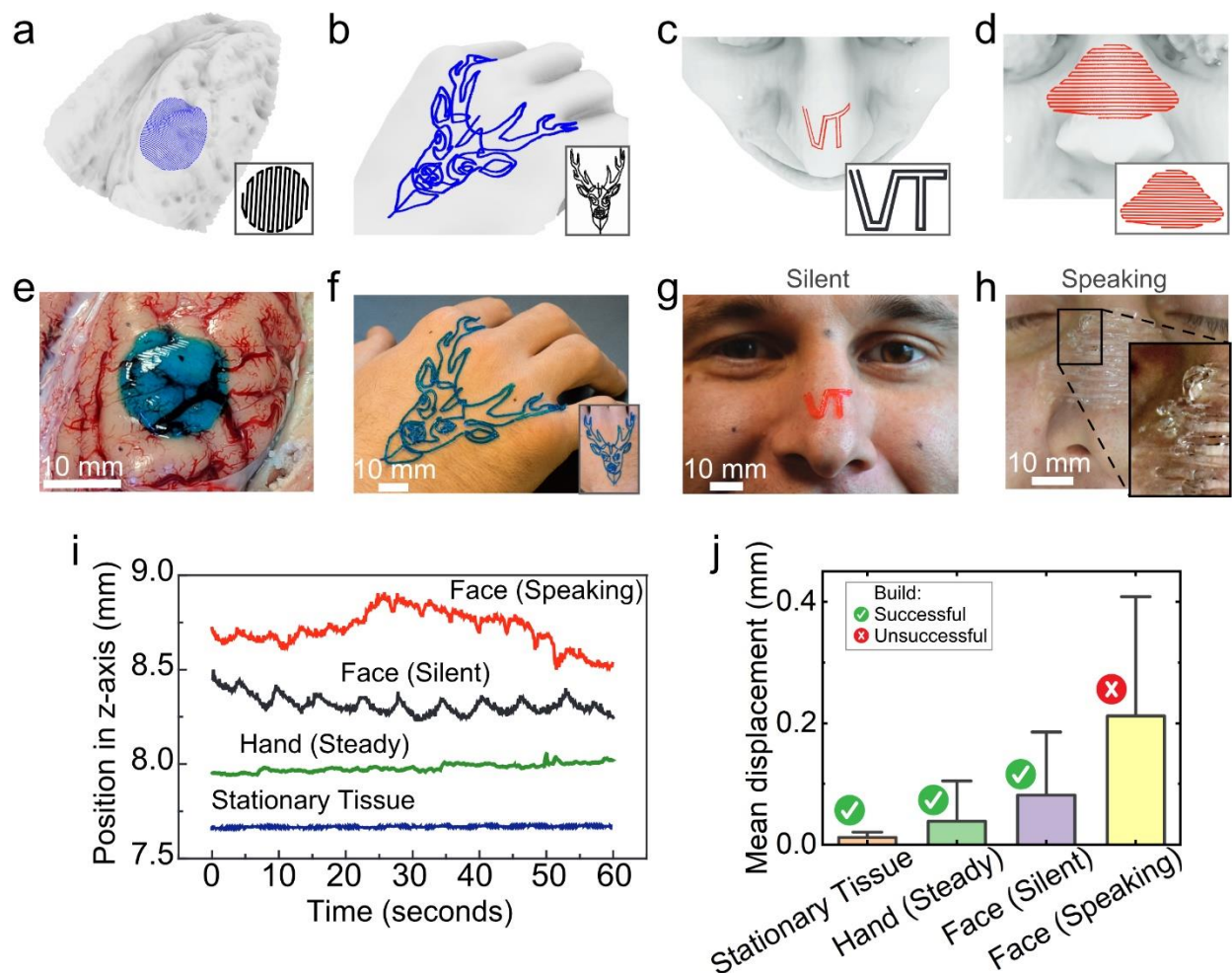


Figure 4.1 Decimated and rendered point cloud data of the porcine brain following the removal of the skull and meninges (a), hand (b), and nose (c-d) with the projected tool path designs onto point

cloud data. Photograph of conformal hydrogel deposition on the brain cortex **(e)**, hand **(f)**, nose **(g)**, and nose while the participant was speaking during 3D printing process **(h)**, using a previous open-loop path planning algorithm for conformal microextrusion additive manufacturing [17]. The real-time vertical displacement **(i)** and mean displacement **(j)** of the stationary tissue, the unconstrained hand, the unconstrained silent face, and the unconstrained face while speaking during 3D printing. Vertical displacement time-series data is arbitrarily shifted for presentation.

4.3.2 Conformal Microextrusion 3D Printing via Real-time Nozzle-Surface Offset Sensing Without the Need for Initial Global Descriptions of Part Geometry

Having established the tolerance of previously utilized 3D scanning-based open-loop path planning methods ($\sim 0.3d$) and need for path planning methods that facilitate additive manufacturing on moving objects, we next established a methodology for conformal 3D printing on moving substrates and objects based on real-time sensing of substrate displacement at the material deposition location (*i.e.*, the nozzle tip). As shown in Figure 4.2, given the tool standoff distance (*i.e.*, the distance between the nozzle and surface) is an important parameter that determines the quality of the conformal 3D printing [183], the z-axis position of the nozzle was controlled in real-time based on the signal from the laser displacement sensor to maintain an optimal tool standoff distance during fabrication. Thus, the closed-loop path planning method compensates for deviations in the tool standoff distance caused by object geometry, tool position, vibrations, or movement.

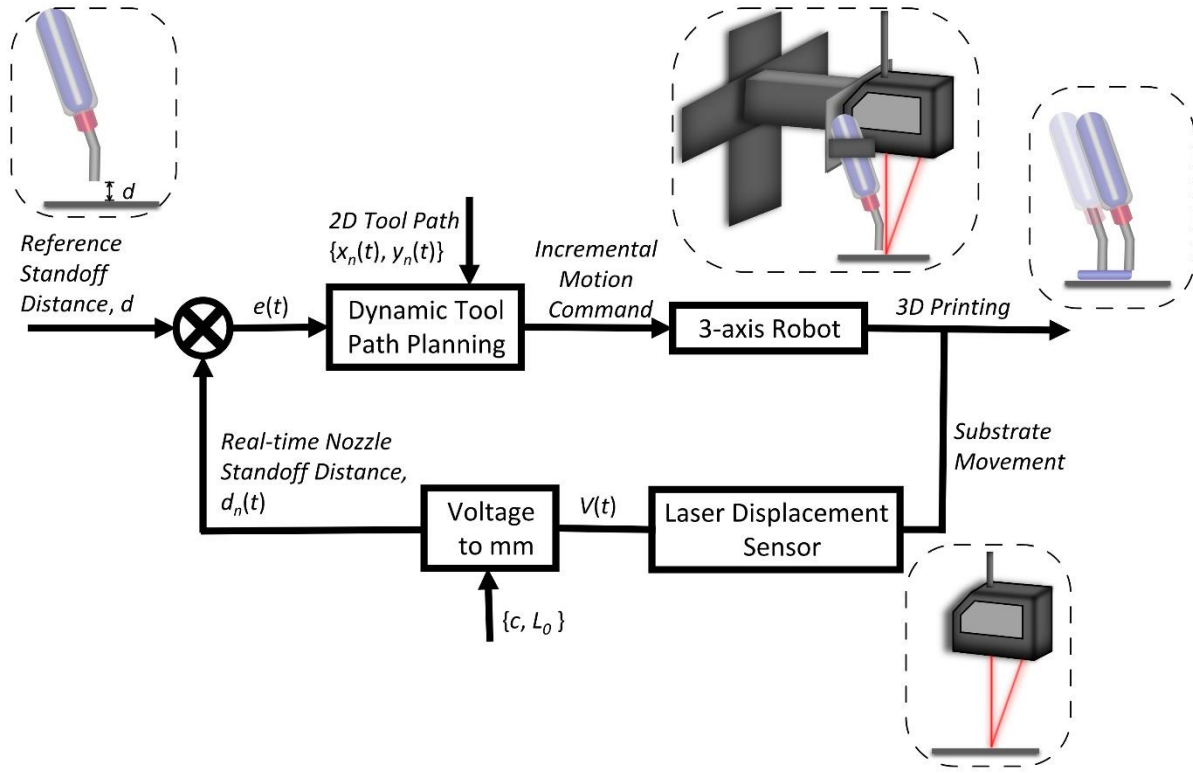


Figure 4.2 Block diagram representation of the feedback loop for real-time vertical nozzle position control during microextrusion 3D printing on moving objects based on real-time localized sensing of nozzle-surface offset.

As shown in Figure 4.3a (and schematically in Figure 4.2), the distance in the x-axis between the measurement location and the center of the microextrusion nozzle, d_s , was set to $r_o + 0.1$ mm in this study. The z-axis nozzle position error, e , is defined as the difference between the optimal (reference) standoff distance, which is dependent on the object geometry and tool trajectory [183], and the measured nozzle-surface offset at a distance of $r_o + 0.1$ mm in front of the nozzle, where r_o is the nozzle outer radius. Hence, the z-axis nozzle position error was adjusted based on the object geometry and tool trajectory to mitigate the filament distortions. As shown in

Figure 4.3b, the tool position was shifted by r_o in the printing direction to avoid flattening of the 3D printed filament by the back of the extruder tip in cases of negative object slope [183], while it was shifted by r_o in the opposite direction to avoid tool-object contact (*i.e.*, collision) by the front of the nozzle in cases of positive slope.

The test parts exhibited a range of slope and curvature as well as upward and downward tool trajectories on inclined and curved surfaces. The polyhedron surface exhibited a change in the z-axis ranging from 6.42 to 12.8 mm, while the change was ranging from 9.14 to 15.6 mm for the spherical surface. The maximum angle of inclination was 54.8 and 50.8°, and the minimum radius of curvature, R , was 0.24 and 0.14 mm for the dimpled-hemisphere and the polyhedron surface, respectively.

As shown in Figure 4.3e-h, the method enabled conformal microextrusion printing of 2D zigzag paths of varying angle α between the lines ranging from 30° to 180° (*e.g.*, straight line) and lengths ranging from 50 to 193 mm. While the trajectory of the laser displacement sensor was offset in the x-direction by d_s , the method enabled the deposition of zigzag paths for the angles $180^\circ \geq \alpha > 30^\circ$ (Figure 4.3e-h). At $\alpha = 30^\circ$, disconnected filaments were observed on the decreasing concave up (Figure 4.3f) and down (Figure 4.3h) surfaces. Therefore, $\alpha = 30^\circ$ was determined as the threshold of quality 2D zig-zag paths on 3D polyhedral and spherical substrates in the absence of part movement with a single 1D displacement sensor.

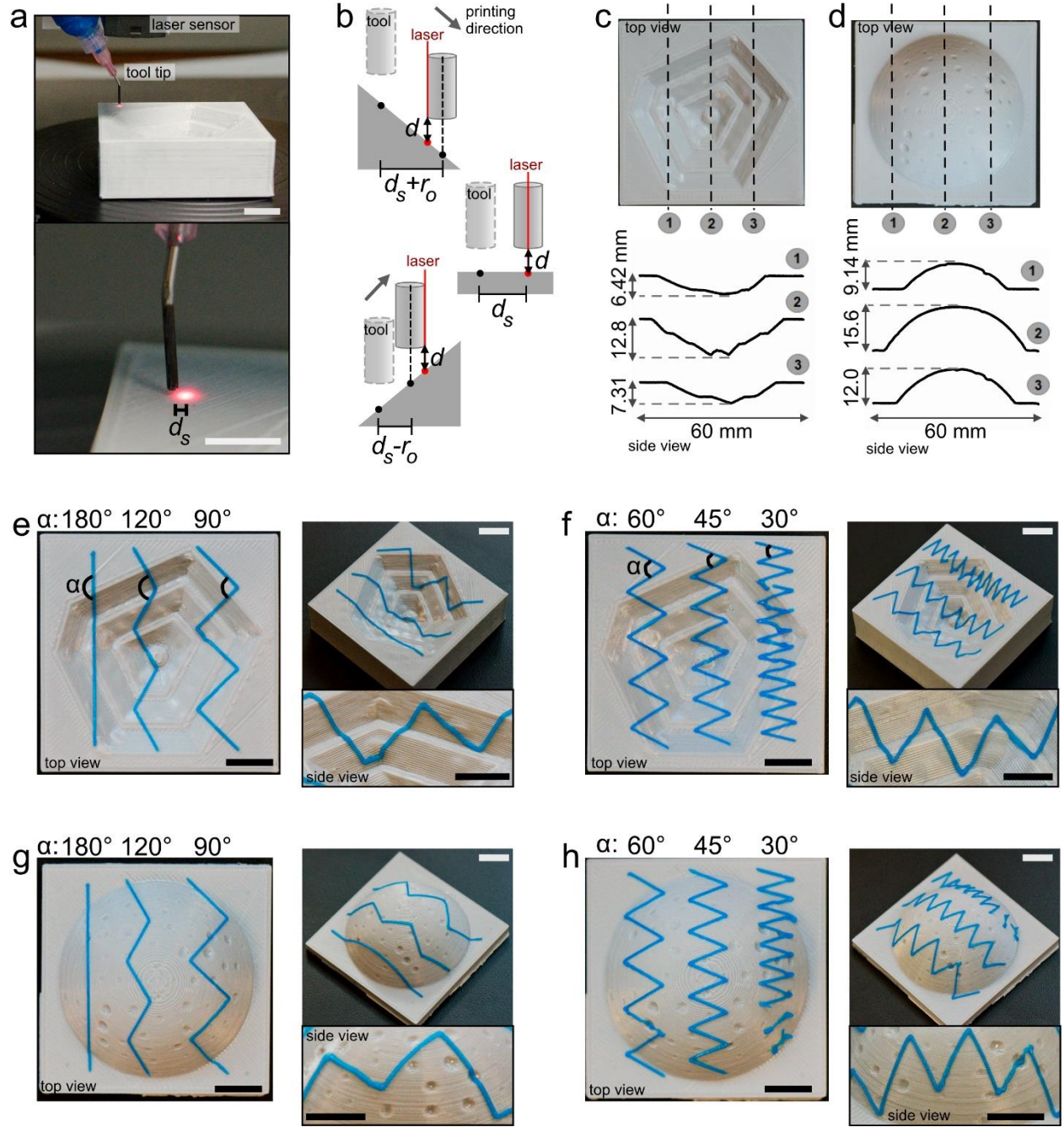


Figure 4.3 Demonstration of the closed-loop controlled path planning method based on real-time nozzle-surface offset sensing for conformal 3D printing on the stationary test parts without the need for initial descriptions of part global geometry (*i.e.*, in the absence of CAD models and point cloud data). **(a)** Photograph and schematic highlighting the sensor-process integration underlying

the closed-loop path planning method. **(b)** Adjustments in the tool position based on the object geometry and the tool trajectory to mitigate filament defects. 3D-printed polyhedral **(c)** and spherical **(d)** test parts and their dimensions in the side view. Conformal 3D printing of hydrogel on the polyhedral **(e)** and the spherical **(g)** objects following the 2D zigzag path designs with $\alpha = 180^\circ, 120^\circ$, and 90° . Conformal 3D printing of hydrogel on the polyhedral **(f)** and the spherical **(h)** objects following the 2D zigzag path designs with $\alpha = 60^\circ, 45^\circ$, and 30° . Scale bars = 10 mm.

The limitation on allowable 2D paths arises from the use of a single laser displacement sensor that is mounted adjacent to the extruder. Thus, the limitation on α and path designs can be relaxed by integrating a rotating stage. To further examine the ability to print multi-directional path designs using the closed-loop path planning method, we next 3D printed multi-layer star-shaped constructs on the aforementioned test parts by rotation of the part during dwell times in the 3D printing process. A five-layer star-shaped construct (edge length = 8.6 mm; thickness of 2 mm) was conformally 3D printed on the polyhedral and spherical test parts. The extruder head was moved only in x- and z-axis. The platform was rotated five times by 72° for each layer. As shown in Figures 4.4a-c and e-g, the closed-loop path planning method was capable of fabricating multi-layered constructs on a nonplanar substrate without the need for a description of the global geometry, such as CAD or point cloud representations. This result demonstrates that the closed-loop path planning method facilitates real-time corrections in nozzle z-axis position that result from both changes in surface height and changes associated with deposition of previous materials (*e.g.*, previous layers of a multi-layered construct). Figures 4.4d and h show the comparison between the desired shape (blue region) and the deposited material (red region) for the polyhedral and spherical parts, respectively. To achieve quality 3D printing, the material width is expected to

be consistent along the path given by the user. The inconsistencies along the path were categorized as overbuild, where the deposited material area was larger than the reference material area, and underbuild, where the deposited material was not enough to cover the reference area. In this study, desired filament width was defined as 1.2 mm and layer thickness as 0.4 mm to enhance the inter-layer adhesion. Hence, the reference filament area was 97 mm^2 for the star path design. The overbuild ratios ($\bar{e}_o$) were 0.109 and 0.117, underbuild ratios ($\bar{e}_u$) were 0.039 and 0.022, and overlap ratios (OR) were 0.961 and 0.979 for the polyhedral and spherical part, respectively. As shown in Figures 4.4d and h, the overbuild and underbuild regions were mostly observed at the corners of the path design where the path starting and ending points intersect, thus the tool extruded through the same point twice on each layer. The data shown in Figures 4.3 and 4.4 suggest that the closed-loop planning method enabled conformal 3D printing on objects without the need for a description of the global object geometry (*e.g.*, via CAD models or point cloud data).

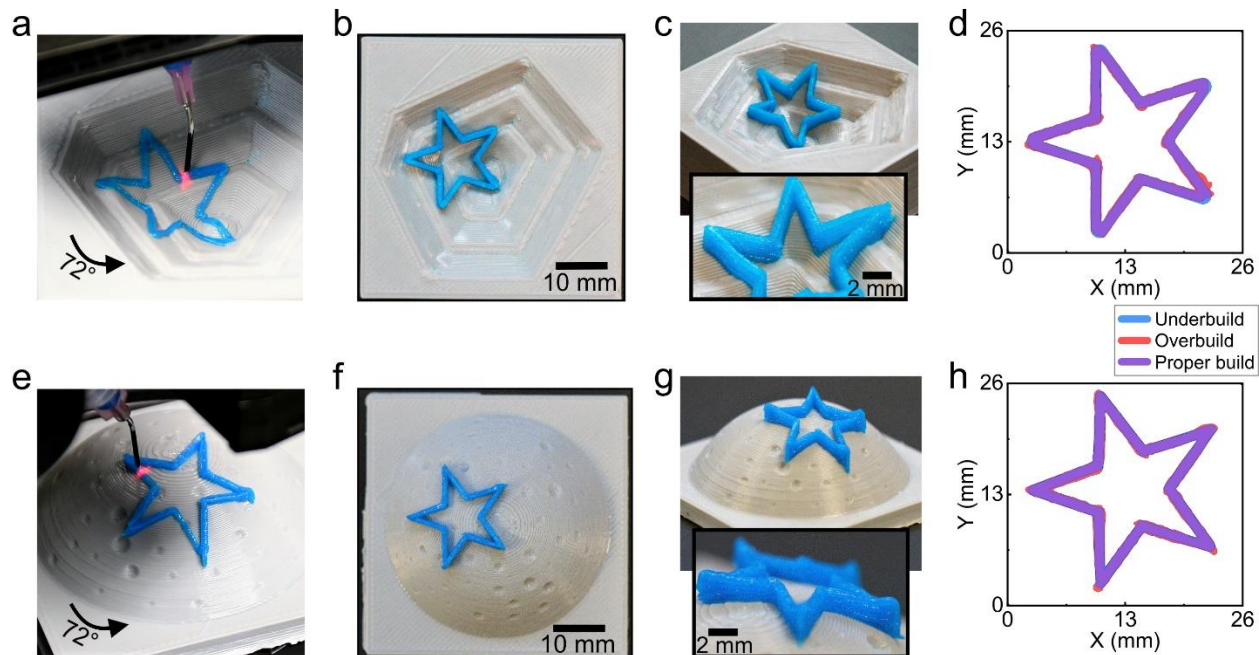


Figure 4.4 Demonstration of the closed-loop path planning method based on real-time sensing of nozzle-surface offset for conformal 3D printing of multi-layered constructs with stage rotation in the absence of global descriptions of part geometry (*e.g.*, CAD models or point cloud data). Photographs highlighting the path planning method showing deposition of the second layer of a 5-layer multi-layered construct on polyhedral **(a)** and spherical **(e)** objects, and the resulting structure on polyhedral **(b-c)** and spherical **(f-g)** objects. Comparison of the 3D printed construct (red region) and the reference design (blue region) for polyhedral **(d)** and spherical **(h)** objects. Overlapping region is represented by purple.

4.3.3 Microextrusion 3D Printing in the Presence of Substrate Vibration

Having established that the closed-loop path planning method based on real-time sensing of nozzle-surface offset enables conformal 3D printing of multi-layer constructs across non-planar stationary objects without the need for global description of object geometry or initial object imaging, we next examined microextrusion 3D printing of multi-layer constructs on moving

substrates and objects (Figure 4.5a). The path utilized to construct a multi-layered triangular construct is shown in Figure 4.5b. A five-layer triangular structure was fabricated based on the path shown in Figure 4.5b, which involved continuous extrusion of material from corner 1 (c_1) to corner 3 (c_3), and from c_1 to c_3 through corner 2 (c_2). The results associated with microextrusion 3D printing on planar substrates oscillating at frequencies of 0.2, 0.4, and 1.3 Hz and amplitudes of 4, 2, and 0.5 mm respectively, are shown in Figure 4.5c-e and Figure 4.6a-f. The frequency and amplitude ranges were selected based on potential applications in additive manufacturing in extreme environments, such as space, and 3D printing in clinical settings, including *in situ* bioprinting. Specifically, the substrate oscillation parameters were selected based on the rate of respiration (0.2 Hz) [75,194], medium-level vibrations onboard the International Space Station (0.4 Hz) [186,195], and the human heartbeat (1.3 Hz) [196,197]. Figure 4.5c-e show the vertical position of the substrate, the z-axis nozzle position error, e , and the tool z-axis position during deposition of the first and final layer. Prior to printing, the tool was positioned with a vertical offset that ranged from 3 - 8 mm from the object to avoid tool-object contact. Hence, the z-axis nozzle position error, e , initially exhibited a large negative value at c_1 , the start of the path (Figure 4.5c-e). The z-axis nozzle position error, e , and the vertical position of the tool were not recorded during the travel without extrusion from the third to the first corner (*i.e.*, c_3 to c_1). As shown in Figure 4.5b, the laser sensor path scanned through the 3D printed layer from the first to the third corner (*i.e.*, c_1 to c_3), while it scanned the part's surface where there was no extruded material along the path c_1 - c_2 - c_3 . The constant difference between the z-axis nozzle position errors along the paths c_1 - c_3 and c_1 - c_2 - c_3 can be seen in data corresponding to Layer 5 in Figure 4.5c-e. Therefore, the total thickness of the previously 3D-printed layers was subtracted from the z-axis nozzle position error,

e , obtained during the 3D printing along the path c_1 - c_2 - c_3 , and then fed to the real-time tool path planning algorithm. Also, the path c_1 - c_2 - c_3 included intersection regions at the first and second corners (*i.e.*, c_1 and c_2) where the laser sensor moved through the previous layers briefly as shown by the junction of the blue and dashed red lines in Figure 4.5b. These intersection regions can be identified in the data corresponding to Layer 5 by the onset of fluctuations in the error, also marked with the first and second corners on the plot (Figure 4.5c-e). As shown in Figure 4.5e, the test part was attached to an inclined platform, and the tool position also reacted to this inclination. The 3D-printed multi-layer structures obtained using the closed-loop path planning algorithm in the presence of substrate oscillation are shown in Figure 4.6a-c. Figure 4.6d-f show the comparison between the desired shape (blue region) and the deposited material (red region) for the 0.2, 0.4, and 1.3 Hz frequencies, respectively. The reference filament area was 105.7 mm^2 for the triangle path design. The overbuild ratios ($\bar{e}_o$) were 0.066, 0.1 and 0.1, underbuild ratios ($\bar{e}_u$) were 0.019, 0.018 and 0.005, and overlap ratios (OR) were 0.981, 0.983 and 0.995 for the frequencies of 0.2, 0.4, and 1.3 Hz, respectively. Similar to the previous observation, the overbuild and underbuild regions were mostly observed at the corners of the path (c_1, c_2, c_3) where the intersection regions were observed. Overall, the structures exhibited a consistent width and thickness at all frequencies and amplitudes tested. The ability to mitigate displacement amplitudes as large as $6.7d$ (*i.e.*, 4 mm) using the closed-loop path planning based on localized surface-nozzle offset sensing represents a significant improvement to that achievable with previously established open-loop processes (see Figure 4.1).

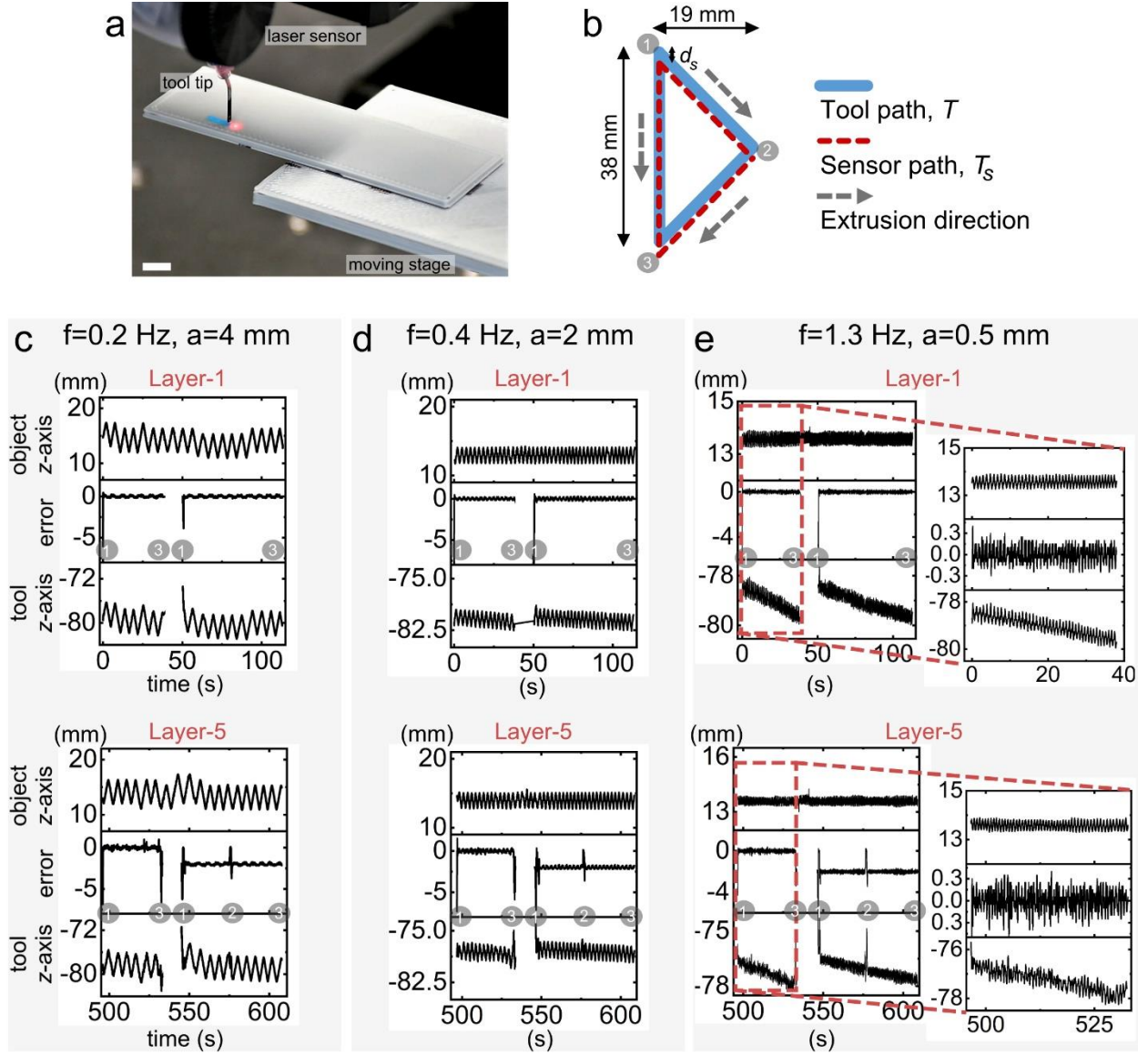


Figure 4.5 (a) Demonstration of the closed-loop path planning method based on real-time sensing of the nozzle (tip)-surface offset for 3D printing on oscillating substrates. **(b)** The triangular tool path design and the laser sensor trajectory. The plots showing the position of the platform, the z-axis nozzle position error, and the tool position in z-axis during the 3D printing of the first and the final layers for the frequencies of 0.2 Hz **(c)**, 0.4 Hz **(d)**, and 1.3 Hz **(e)**.

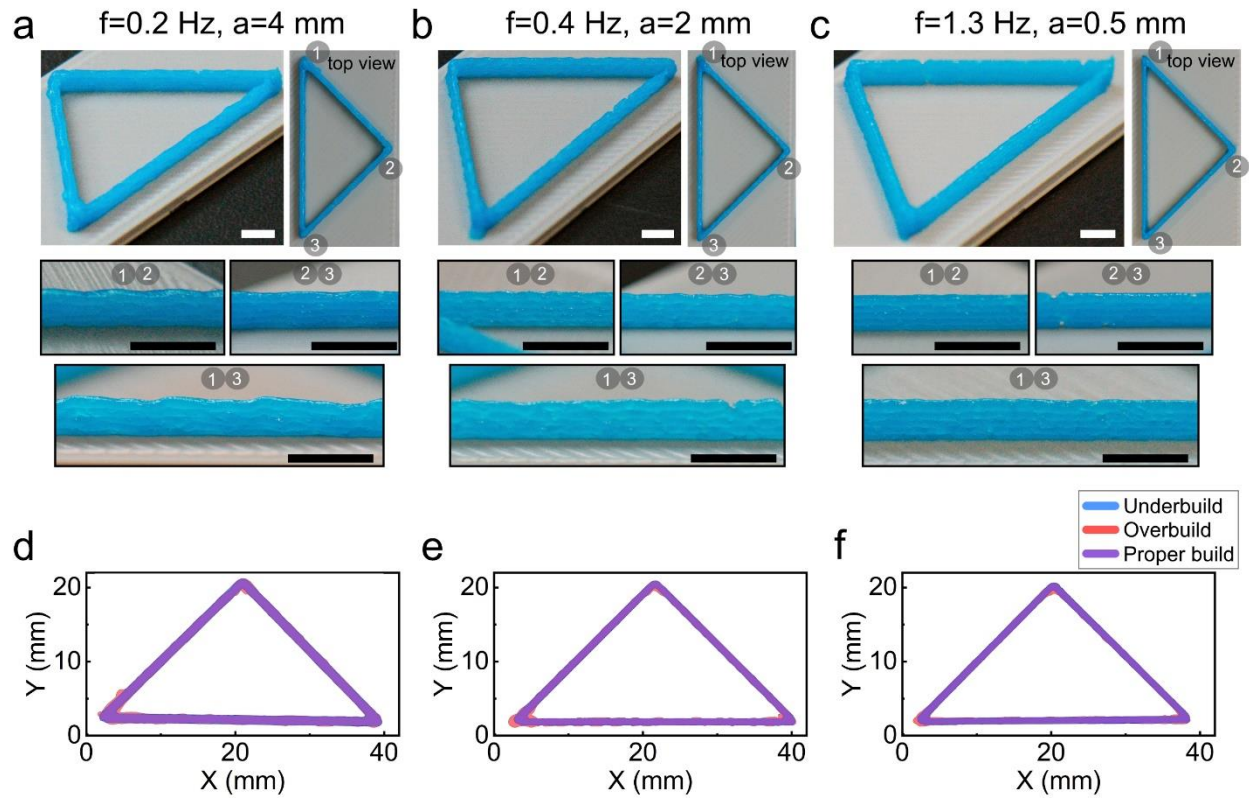


Figure 4.6 The photographs of the resulting multi-layer triangular structure 3D printed on the oscillating test part with the frequencies of 0.2 Hz **(a)**, 0.4 Hz **(b)**, and 1.3 Hz **(c)**. Comparison of the 3D printed construct (red region) and the reference design (blue region) for the frequencies of 0.2 Hz **(d)**, 0.4 Hz **(e)**, and 1.3 Hz **(f)**. Overlapping region is represented by purple. Scale bars = 5 mm.

4.3.4 Conformal In Situ Bioprinting on Moving Human Anatomy

Having demonstrated that closed-loop controlled tool path planning based on real-time sensing of tool-surface offset enables conformal 3D printing on planar substrates that oscillate 0.2 – 1.3 Hz, we next examined the potential for *in situ* conformal additive manufacturing of single- and multi-layer hydrogels constructs on an adult human hand in the presence of vertical hand

motion (Figure 4.7a-b). Thus, the nozzle z-axis position was updated in real-time based on deviations in nozzle-surface offset associated with changes in object height during lateral path motion, accumulation of previously printed material (*i.e.*, layers), and hand motion. The hand was unconstrained on a custom moveable platform and moved arbitrarily in z-axis within the dynamic range of the 1D laser displacement sensor (25 mm). No additional measures were taken to prevent lateral movement of the hand. A photograph of the 3D-printed five-layer triangular and single-layer filled square constructs on the hand obtained using the closed-loop tool path planning method in the presence of random vertical hand movement are shown in Figures 4.7c and e. Figures 4.7d and f show the vertical position of the hand, the z-axis nozzle position error, e , and the tool z-axis position during the printing process of the multi-layer triangular and filled square constructs, respectively. Similar to printing on oscillating planar substrates, the tool was initially positioned with a vertical offset of 3-8 mm from the object in the absence of extrusion to avoid tool-object contact. The tool only extruded material when it moved in positive x-axis direction because of the sensor position (*e.g.*, c_1 - c_3 , c_1 - c_2 - c_3 , c_4 - c_5 paths). Hence, the z-axis nozzle position error e exhibited initially a large negative value at c_1 (Figure 4.7d) and c_4 (Figure 4.7f) which can be identified in the plots as marked by circled numbers. The z-axis nozzle position error e and the vertical position of the tool were not recorded during the paths c_3 - c_1 and c_5 - c_4 . The sensor path and the sensor feedback for the triangular structure exhibited similar properties, such as the layer thickness difference and the intersection regions at c_1 and c_2 , as described for 3D printing on planar oscillating substrates. The effect of the hand geometry (*e.g.*, slope) on the response of the closed-loop tool path planning method can be observed at 20-30 seconds by comparing the position of the hand and the tool (Figure 4.7f). In summary, the real-time correction to the tool position enabled

in situ conformal additive manufacturing on arbitrarily moving human anatomy without prior the need for a description of the global geometry via CAD models or point cloud data. As a result, this work established a novel closed-loop path planning method that enables real-time corrections in nozzle-surface offset based on changes that may potentially arise from nonplanar anatomical structures, previously deposited material, and voluntary or involuntary human motion.

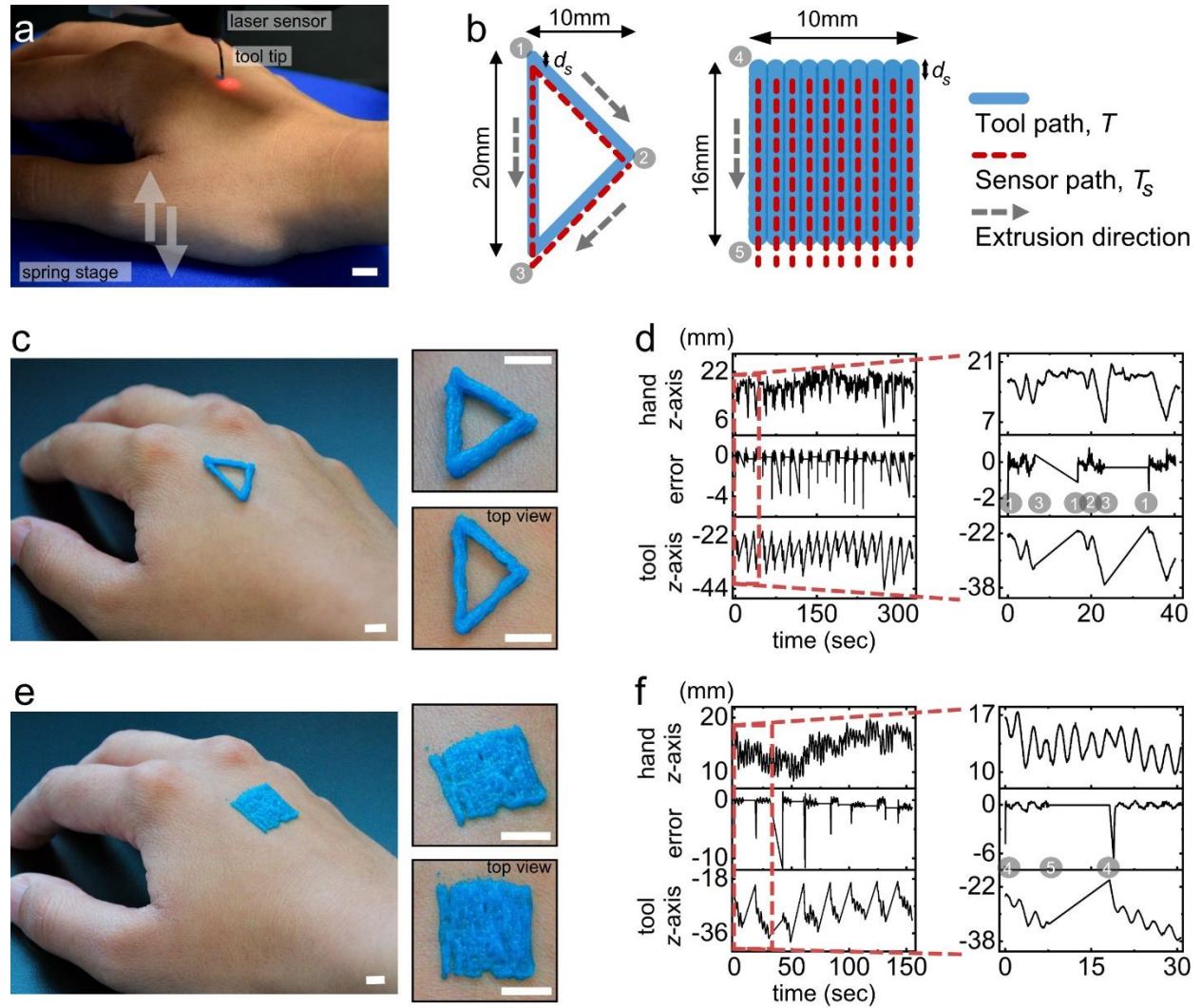


Figure 4.7 (a) The photograph showing the closed-loop controlled conformal microextrusion additive manufacturing on the skin of an adult human subject with a spring platform during the process. (b) The four-layer triangular and the single-layer filled square tool path designs and the

related laser sensor trajectories. The photographs of the resulting multi-layer triangular **(c)** and the single-layer filled square **(e)** structures 3D printed on the arbitrarily moving hand. The plots showing the vertical movement of the hand, the z-axis nozzle position error, and the tool position during the deposition of the multi-layer triangular **(d)** and the single-layer filled square **(f)** structures in the presence of arbitrary movements. Scale bars = 5 mm.

4.4 Conclusion

Here, we provide a novel closed-loop controlled path planning method for microextrusion 3D printing based on real-time sensing of the local nozzle offset that enables conformal 3D printing on moving objects and human anatomy without the need for initial descriptions of part geometry, such as via CAD models or imaging data. The threshold of a previously established open-loop point cloud-driven path planning method for object movement was characterized ($\sim 0.3d$), identifying the demand for methods based on real-time sensing and control of nozzle-surface offset. The novel closed-loop path planning method based on local sensing of nozzle offset was validated by 3D printing on oscillating substrates and *in situ* conformal microextrusion additive manufacturing on moving human anatomy and enabled mitigation of displacements during manufacturing as large as $6.7d$. This work also provides an approach for conformal microextrusion 3D printing and *in situ* bioprinting on freeform surfaces and moving human anatomy without the need for reverse engineering or pre-characterization of the object geometry. This closed-loop path planning methodology can also potentially support quality-controlled additive manufacturing of parts that undergo shrinkage or other types of geometry change during fabrication by real-time adaptation of tool path based on localized tool-part offset sensing.

4.5 Supporting Information

This supporting information document contains: 1) pseudocodes for synchronous (Table S4.1) and asynchronous (Table S4.2) path planning program codes used for closed-loop controlled conformal 3D printing; and 2) a figure showing the porcine brain after skull removal.

Table S4.1: Path planning program code used for 3D printing multi-layered star-shaped construct on nonplanar substrates.

```

Input:  $[T]_{5,3}$ : A list of start points for each corner of the star path design
 $L_s$  : Length of the edges of the star
 $L_g$  : Length of the gap between the edges in the same direction
 $d$  : nozzle diameter
 $Pos_x$  : Position feedback of x-axis obtained by motion controller
 $V$  : Voltage output from the laser sensor
Initialize  $e, Lay, m$ 
 $Lay \leftarrow 0$  /*Layer thickness*/
for each layer do
  for each corner  $i$  in  $T$  do
    F 10 /*federate in mm/s*/
    ABSOLUTE /*motion command type*/
    LINEAR X  $T_{i,x}$  Z  $T_{i,z} + Lay$  /*linear motion command*/
    INCREMENTAL /*motion command type*/
     $e \leftarrow V * 5 - 13$  /*convert voltage to mm*/
    LINEAR Z  $e$ 
    Extrusion pressure ON
    F 2.5
    while  $Pos_x \leq T_{i,x} + L_s$  do
      if  $Pos_x = T_{i,x} + L_s + L_g$  or  $Pos_x = T_{i,x} + 2L_s + L_g$  then
        Extrusion pressure OFF
      end if
       $e \leftarrow V * 5 - 13$ 
       $m \leftarrow e / 0.1$ 
      if  $m > 0.2$  then
        LINEAR X 0.1 Z  $e$ 
      else if  $m < -0.2$  then
        LINEAR X 0.1 Z  $e / 10$ 
      else
        LINEAR X 0.1 Z  $e / 5.5$ 
      end if
      if  $Pos_x = T_{i,x} + 2L_s$  then
        Extrusion pressure ON
      end if
    end while
    Extrusion pressure OFF
    F 10
    LINEAR Z 20
    rotate the stage by  $72^\circ$ 
  end for
   $Lay \leftarrow Lay + d$ 
end for
LINEAR Z 30
END PROGRAM

```

Table S4.2: Asynchronous closed-loop path planning program code used for 3D printing filled pattern on moving human hand.

```

Input:  $[T]_{20,3}$ : The start point of each line in the filled pattern
 $L_s$ : Length of the lines in x-axis direction
 $d$ : nozzle diameter
 $Pos_x$ : Position feedback of x-axis obtained by motion controller
 $V$ : Voltage output from the laser sensor

Initialize  $e$ 
for each line  $i$  in  $T$  do
    F 10 /*federate in mm/s*/
    ABSOLUTE /*motion command type*/
    LINEAR X  $T_{i,x}$  Y  $T_{i,y}$  Z  $T_{i,z}$  /*linear motion command*/
    INCREMENTAL /*motion command type*/
     $e \leftarrow V*5 - 13$  /*convert voltage to mm*/
    LINEAR Z  $e$  ZF20 /*linear motion command with federate of 20 mm/s in z-
axis*/
    Extrusion pressure ON
    MOVEINC X  $L_s$  2.5 /*asynchronous motion command with federate of 2.5
mm/s*/
    while  $Pos_x \leq T_{i,x} + L_s$  do
        if  $Pos_x = T_{i,x} + L_s$  then
            Extrusion pressure OFF
        end if
         $e \leftarrow V*5 - 13$ 
        LINEAR Z  $e$  ZF20
    end while
    Extrusion pressure OFF
    WAIT MOVEDONE X /*wait until asynchronous motion is completed*/
    ABSOLUTE
    LINEAR Z0 ZF20
end for
END PROGRAM

```



Figure S4.1 The exposed porcine brain after removing a region of the skull ($\sim 60 \text{ cm}^2$) using three sloped manual cuts with a hand saw (24 TPI). The meninges was removed on the right hemisphere.

5 Automated Characterization of Bulk Tissue 3D Spatial Material Properties

Here, we report a novel method for automated characterization of bulk tissue 3D spatial properties based on reverse engineering-driven non-planar tool path planning and robotically-directed sensing. The method incorporates information on object (e.g., tissue) and inspection tool (e.g., sensor) geometry for automated inspection of tissue mechanical and dielectric properties across macroscopic nonplanar domains as large as 44 cm² without the need for manual processes, such as sensor-tissue integration. The impact and the utility of the method were demonstrated by automated mapping of 3D spatial distributions of mechanical and dielectric properties of plant and animal tissues using multiple complementary impedimetric-based sensors of varying types and form factor, including rigid micro-electromechanical systems and flexible multi-functional fibers. Applications to automated characterization of food quality (e.g., type and age) are provided, including 3D spatial mapping of plant (fruit) and animal tissue mechanical and dielectric property distributions. In summary, we report here an automated method for characterizing the 3D spatial distributions of tissue mechanical and dielectric properties via robotically-directed sensing and real-time impedimetric monitoring. This work provides a new method for automated characterization of bulk, macroscopic tissues, and soft object material property distributions via nonplanar path planning and robotically-directed sensing that can benefit quality-control and – assurance across various industries as well as support fundamental research associated with tissue and organ engineering, healthcare, and manufacturing.

5.1 Introduction

Automated inspection methods provide economical, convenient, and accurate quantitative analysis of samples and products in various industries including agriculture, pharmaceutical, and biotechnology [198–200]. Commonly, fluorescence microscopy is used as a noninvasive inspection tool in life-science studies as it enables the visual inspection of biological specimens with sizes ranging from submicrometers to millimeters [201]. However, recent developments in biotechnology have shifted the focus of inspection from molecular and cellular products to tissue-based systems and products, including mesoscopic (i.e., millimeter to centimeter) and macroscopic tissues and organs [76–78]. The applicability of fluorescence imaging techniques to the inspection of bulk macroscopic tissues is relatively limited because of the strong absorption and scattering of light by the biological samples [79]. Therefore, there is a need for the development of new automated inspection techniques that enable the characterization of large biological specimens, such as the spatial distribution of tissue properties. Impedimetric sensing methods have emerged as versatile measurement format for quantification and monitoring of various tissue characteristics, including composition [80–82], cell viability [86], cell type [87], extent of differentiation [88,202], chemosensitivity [89], and organ assessment [90]. Thus, impedimetric sensing can be leveraged for monitoring various tissue characteristics, properties, and physiological processes.

Ensuring the quality and safety of macroscopic tissue-based products are essential in various areas including the food industry [91], tissue engineering [93,94], and organ transplantation [95]. Sensing of tissue impedance via surface contact electrodes, often referred to as bioimpedance monitoring, has been leveraged for the assessment of health and quality of animal and plant tissues, such as engineered animal and plant tissues and foods, as it enables monitoring

of tissue composition, structure, and physiological processes [91,92,203–205]. Electrical Impedance Spectroscopy (EIS) via surface-based two- and four-electrode configurations has been used as a non-destructive inspection method to characterize various fruits and vegetables including apples, bananas, lettuce, mangoes, and strawberries [92,203]. For example, Chowdhury et al. showed that the electrical impedance of bananas was correlated with the ripening process by analyzing impedance and phase angles in a frequency range from 50 Hz to 1 MHz for 6 days [204]. Yovcheva et al. argued that the changes in the electrical properties of the apples can be attributed to the changes in the relative moisture content during aging [205]. They performed impedance measurements in a frequency range from 30 Hz to 30 MHz on the cylindrical samples cut from the apples with a length of 46 mm and a diameter of 20 mm. Ibba et al. evaluated the impedance changes on apples and bananas for 13 days and showed the relationship between fruit ripening and the impedance in a frequency range from 100 Hz to 85 kHz [203]. They used a total of four electrodes placed at a 3 cm distance and then averaged the measurements obtained from multiple two-electrode configurations to achieve an output representing the entire fruit. Also, Mousa et al. showed the effect of the freezing and heating injuries on the bioimpedance of several vegetables including tomatoes, eggplants, and cucumbers over a frequency range of 10 Hz to 200 kHz using 2 electrodes-configuration [206]. Narayanan et al. used bioimpedance spectroscopy to characterize 3D bioprinted constructs in terms of cell viability and proliferation during and after the bioprinting process in a frequency range from 50 kHz and 20 MHz using a dielectric impedance spectroscopy flush probe [207]. Using the same probe and frequency range, Shohan et al. combined dielectric impedance spectroscopy and supervised machine learning to monitor the changes in cell viability and proliferation on the 3D printed scaffolds seeded with human adipose-derived stem cells during

the biofabrication and maturation [208]. Haring et al. utilized impedimetric sensing for in-line monitoring of the bioink composition, such as cell viability and type, during the 3D bioprinting process over a frequency range of 10^2 - 10^6 Hz using 2 electrodes-configuration [202]. Recently, Yoshimoto-Haramura et al. used bioimpedance measurements to predict the percentage of liver steatosis which is considered a main reason for graft failure after transplantation at multiple frequencies ranging from 2 to 100 kHz using a Fish analyzer DFA 100 which is based on the tetrapolar circuit method [209].

Although bioimpedance monitoring enables noninvasive and real-time characterization of bulk macroscale tissues and organs, the majority of measurement formats are performed either at a single location and do not yield spatial information [210]. However, there remains a need to verify the spatial distribution of tissue bioimpedance [210], in addition to other tissue properties. Scanning electrochemical microscopy (SECM), microelectrode arrays (MEA), and electrical impedance tomography are among the spatial impedimetric sensing methods that have been developed and used in various studies [210]. However, these methods cannot be applied to generate 3D property maps for characterization of the samples with freeform surfaces, since their applications are limited to samples with flat surfaces, 2D impedance maps, and the use of fixed multiple-electrodes probes [210,211]. To address this challenge, conforming thin film-based systems have been utilized for spatial mapping of bulk tissues and organs [212], yet require manual tissue handling processes associated with sensor-tissue integration. Hence, it is essential to develop flexible and automated methods capable of providing mapping of bulk tissue and organ 3D spatial properties that require minimal manual processes (e.g., associated with sensor-tissue integration) and requirement for sensor-tissue integration prior to characterization.

The reliability of automated tissue inspection methods depends on precise control of the sensing tool's position since the performance of electrical impedance measurements relies on the contact area between the sensing electrodes and the specimen [213]. Therefore, manual position control of the sensing tool limits the accuracy and reliability of the sensing system [213]. Recently, several researchers have investigated robot-assisted electrical impedimetric-based sensing systems [211,213]. For example, Cheng et al. presented an electrical impedimetric-based system that generates cross-sectional 2D impedance maps for detection of heterogeneous elements under the sample's surface by scanning the target area given by the user [211]. Penza et al. incorporated a stereo vision system to control the motion of the robotic system for electrical impedimetric-based scanning of a target tissue surface to discriminate the tumor location [213]. Even though path planning for electrical impedimetric-based scanning applications is an emerging area, computer-aided inspection planning for touch-based probes and coordinate measuring machines (CMM) has been widely studied for automated inspections of manufactured parts [17]. The main constraint in inspection path planning is collision detection and automatic avoidance of obstacles since the sensing tool or tool holder may collide with the sample and damage both the tool and sample [17,20]. Various approaches have been proposed to generate collision-free scanning paths for CMMs [17–21]. For example, Zhao et al. combined a laser scanner and a touch-trigger probe to create collision-free inspection plans for CMM using the product and manufacturing information data contained in the computer-aided design (CAD) model of the part [18]. Later, Mineo et al. proposed a Mesh Following Technique to generate tool paths directly from the points on the tessellated model (i.e., mesh) without curve fitting and approximation steps [19]. Recently, Liu et al. presented an optimal path planning system that minimizes the total inspection time for free-

form auto body surfaces using simulated annealing-based optimization algorithm [20]. However, CAD or mesh models containing the topographic information of the part are required inputs for the inspection path planning applications. Reverse engineering (RE) techniques, such as 3D scanning, computed tomography, and magnetic resonance imaging, are utilized to obtain 3D models of organs or other anatomical structures in the absence of an existing CAD model [61,63]. Thus, new methods for inspection path planning that synergize with 3D scanning-based reverse engineering workflows could enable the spatial impedimetric characterization of macroscale tissues and organs with freeform surfaces. In addition, there remains a need to characterize additional properties, such as mechanical properties [93].

Here, we report a novel method for automated characterization of bulk tissue and organ 3D spatial properties based on reverse engineering-driven non-planar tool path planning and robotically-directed sensing. Our adapted point cloud-based path planning (PCPP) algorithm generates a customized sensing path based on the tissue surface geometry acquired by the 3D scanning system, enabling spatially resolved high-throughput sensing across the inspection area specified by the user. We demonstrate automated 3D spatial mapping of bulk tissue impedance and mechanical properties using real-time impedimetric monitoring via multifunctional fiber and piezoelectric cantilever sensors, respectively. Importantly, the method provides automated characterization of tissue 3D spatial material properties without the need for manual handling processes associated with sensor-tissue integration. Applications to inspection of food quality were provided, including potential for automated inspection of meat and fruit type, composition, and age. This work provides an advance in automated methods for inspection, and monitoring of bulk tissues via characterization of tissue and organ bulk 3D spatial properties via robotically-

directed sensing, which reduces the need for manual tissue handling and requirement for sensor-product interface prior to characterization.

5.2 Materials and Methods

5.2.1 Materials

Lead zirconate titanate (PZT-5A; $72.4 \times 72.4 \times 0.127\text{mm}^3$) with nickel electrodes was purchased from Piezosystems (Woburn, MA). Borosilicate glass was purchased from VWR. Glass cylinders and ethanol (200 proof) were from Fisher Scientific. Polyurethane (Fast-Drying) was from Minwax. Epoxy (EA 1C-LV) and cyanoacrylate (409 Super Bonder) were from Loctite. Polycarbonate (PC) film was from Laminated Plastics. Medical epoxy (EA M-121HP) was from Henkel Loctite. Silver paint was from SPI Supplies. Vinyl acetate tubing (0.5 mm inner diameter) and polyvinylidene fluoride was from McMaster-Carr. 5-minute epoxy was from Devcon. Ultrapure deionized water (DIW) was from a commercially-available DIW system (Direct-Q 3UV; Millipore). Polylactic acid (PLA) filament was purchased from LulzBot. Pluronic F-127 (PF127) was from MilliporeSigma. Silicone (SI 595 CL) was from Loctite.

5.2.2 Sensor Fabrication

Piezoelectric-excited millimeter cantilever (PEMC) sensors and multifunctional fiber impedimetric sensors were selected for spatiotemporal sensing of animal and plant tissue mechanical properties and bioimpedance characteristics (e.g., dielectric property), respectively. PEMC sensors were fabricated from lead zirconate titanate (PZT) and borosilicate as described in previous studies [214,215]. The resulting PEMC sensor exhibited a rectangular geometry of $3 \times 1 \times 0.127 \text{ mm}^3$ (L - w - t), where L , w , and t represent the cantilever length, width, and thickness,

respectively. Hollow multifunctional fibers were fabricated using PC films and copper wire (16 gauge) as described in previous studies [202,216]. The resulting hollow fiber sensors exhibited a cylindrical geometry with a diameter of 0.5 mm and a length of 20 mm. Copper electrodes were exposed on both ends of the fiber. The sensing devices were affixed to a three-axis robot (MPS75SL; Aerotech) for the spatiotemporal biosensing process.

5.2.3 Measurement Principle and Data Acquisition

The resonant frequency (f_n), phase angle at resonance (ϕ_n), and impedance (Z_n) at resonance of PEMC sensors were continuously monitored with a vector-network analyzer with an impedance option (E5061b-005; Keysight). The sensor's dynamic mechanical response, here, the frequency response, was obtained via electromechanical coupling effects using electrical impedance analysis, which provides the electrical impedance magnitude ($|Z|$) and phase angle (ϕ) spectra of the piezoelectric layer ($|Z|$ and ϕ vs. frequency (f), respectively). Electrical impedance analysis was performed using a stimulus amplitude of 100 mV AC and zero DC bias across a frequency range $f_n \pm 10$ kHz. Sensor signals (f_n , ϕ_n , and Z_n) were acquired in real-time using a custom MATLAB program.

The impedance response of the multifunctional fiber sensors was monitored using a potentiostat (Interface 1010E, Gamry Instruments) using a two-electrode format. The two copper electrodes served as the working and counter electrode. The electrical impedance response of the system, which provides the electrical impedance magnitude ($|Z|$) and phase angle (ϕ), was obtained at 10 kHz using an AC voltage of 10 mV and zero DC offset with a sample time of 1 s. The fixed

monitoring frequency (10 kHz) was selected as previous studies on bioimpedance analysis on tissues and cells suggest that the maximum relative difference is observed at 10-20 kHz [202,217].

5.2.4 Spatiotemporal Sensing Process using Point Cloud-based Path Planning

Previously reported Point Cloud-based Path Planning (PCPP) algorithm for non-planar 3D printing process [183] was modified to generate a collision-free path planning for inspection of free-form surfaces. The workflow of the proposed methodology consisted of 3 steps: point cloud generation, registration and preliminary path planning, and collision detection and corrections.

5.2.5 Point Cloud Generation

The point cloud generation process started by placing three user-defined reference points (~1 mm diameter) around the perimeter of the object using removable stickers or a black marker, or by placing the object on a pre-marked stage. The object was then scanned using a single camera-projector structured-light scanning system (HP 3D Structured Light Scanner Pro S2; HP) to acquire the point cloud data following our previously reported protocols [47,49,167,168]. The objects were scanned by performing 1 to 4 scans over a 360° rotational angle to capture the surface geometry from various angles depending on the geometric complexity of the part. The point cloud data could be acquired in a single scan if it spans the required sensing area on the part and the reference points. The point cloud input to the algorithm is required to encompass the reference points, span the entire sensing domain, and have sufficient density to effectively represent the surface features. Later, the point cloud data was converted into a triangulated mesh file representing the surface topography of the object. The resulting mesh surface (**S**) was then transferred to the computer-

aided design (CAD) software (Rhino 6), which here served as a platform for the implementation of the reverse engineering-driven tool path planning program.

5.2.6 Registration and Preliminary Conformal Path Planning

The developed algorithm was implemented using the RhinoScript tool of Rhinoceros 6 software. 2D filled path was generated to encompass the sensing domain given by the user and placed above the point cloud representation of the object using a custom program implemented in Rhino 6. The user-defined filled path consisted of continuous lines and curves. The PCPP program commenced with a registration process that aligned the mesh surface (S) and user-defined path to the robot's reference frame and then projected the user-defined planar path onto the mesh surface in the z-axis direction as described in the Chapter 3 [183]. The output of the registration step in the program was a tool path (T^a) on the mesh surface, scanning through the user-defined inspection area with a zigzag pattern, and reference frame-aligned mesh surface S^a . The pseudo-code is provided in Algorithm 1 of Section 3.6.

Following the registration and projection steps, inspection sampling distance (h), safety distance (d), and sensing tool geometry were obtained from the user by the program. The measuring points ($\mathbf{M}$) on the free-form surface of the object were then generated by dividing the path curve (T^a) based on the sampling distance (h) given by the user (*i.e.*, 1 measuring point per h). The sampling distance was set 2 – 5 mm throughout the study. The i^{th} point in $\mathbf{M}$ is denoted by $m_i = (x_i, y_i, z_i)$ $i = 1, 2, \dots, l$ where $l = \lfloor L_p/h \rfloor + 1$. Next, the tool path curve (T^a) was discretized to generate motion commands capable of resolving the path, resulting in an array of tool path points, $\mathbf{T}$. The path density was determined by the metric of two path points per sensing tool width (w).

The j^{th} point on $\mathbf{T}$ is denoted by $p_j = (x_j, y_j, z_j)$ $j = 1, 2, \dots, k$ where $k = \lfloor 2L_p/w \rfloor + 1$, where L_p is the total length of the user-defined path (i.e., k points along the path). In this study, the width of the cantilever sensor was taken as the length of its longest edge (1 mm), and the width of the fiber sensor as its diameter (0.5 mm). The path points in $\mathbf{T}$ were then offset from the surface along the z-axis direction by a safety distance d given by the user. The output of this step of the program is the preliminary tool path points $\mathbf{T}$ and the measuring points $\mathbf{M}$.

5.2.7 Collision-free Conformal Path Planning

Given that the inspection process requires collision-free path planning, the program runs a collision detection and correction step based on the surface features of the object and the sensing tool geometry. If a collision is detected, the path points in $\mathbf{T}$ are offset from the surface by modifying the x- and y-axis coordinates to avoid a collision. Specifically, the path planning program utilizes the mesh surface representing the surface topography (S^a), the tool path points ($\mathbf{T}$), the sensing tool geometry as input parameters, and outputs collision-free path points conforming to the free-form surface ($p_j, p_{j+1}, \dots, p_{j+n}$) that connects two consecutive measuring points (m_i and m_{i+1}), where $n = 2h/w$. This part of the program started by determining the infeasible inspection points (i.e., locations) that cannot be reached by the sensing tool whose workspace is constrained by the tool geometry and the 3-axis cartesian robot. Two polysurfaces G and Q was generated to simulate the tool and tool holder geometry, respectively by the program. The center of the tool tip was positioned at each inspection point m_i to examine if there is an intersection between the tool holder geometry (Q_i) and the mesh surface (S^a) representing the object geometry. Thus, if the program detected a potential tool-surface collision at a given measuring point, that point m_i was removed from the feasible measuring points array $\mathbf{M}$. To ensure contact between the

sensor and the surface at the measuring points, the feasible measuring points (m_i) were offset towards the object by 0.5 mm in the z-axis direction. Next, potential collisions were detected across the tool path points in $\mathbf{T}$. Similar to the infeasibility detection method, the tool geometry (G) was positioned along the path to simulate the tool motion in a way that the center of the tool tip was placed at each p_j in $\mathbf{T}$ to detect interference between the tool (G_j) and the object surface (S^a). If the program detected a potential collision at a path point p_j , then the path point was moved laterally away from the surface by L_j in the direction of $-\vec{V}_j$ to avoid interference between the tool and the surface. L_j was calculated as the distance to achieve a lateral safety gap of 0.1 mm between the closest points on the surface and the tool.

$$V_j = \overrightarrow{p_j, c_j} \quad (18)$$

$$r_j = |p_j, q_j|, \quad q_j \in \{G_j \cap \overline{p_j + M\vec{V}_j}\} \quad (19)$$

$$L_j = r_j - |p_j, c_j| + 0.1 \quad (20)$$

where c_j is the centroid of the intersection points list $\{G_j \cap S^a\}$, and M is a number greater than the tool width w . The corrected path points in $\mathbf{T}$ were calculated based on two cases determined by the tool-object intersection:

Case1: There exists no intersection between G_j and S^a .

$$p_j = p_j \quad (21)$$

Case2: There exists an intersection between G_j and S^a .

$$p_j = p_j + L_j \vec{V}_j \quad (22)$$

The flowchart of the overall methodology is provided in Figure 5.1f. The output of the program was a collision-free conformal path planning for spatiotemporal sensing, including the measuring points **M** and travel points between the measuring points **T**. For a collision-free path from m_i to m_{i+1} , the tool follows the path $p_j \rightarrow m_i \rightarrow p_j \rightarrow p_{j+1} \rightarrow \dots \rightarrow p_{j+n} \rightarrow m_{i+1} \rightarrow p_{j+n}$ and waits t seconds at each measuring point to collect the sensor response. The wait time t was set as 15 seconds for both PEMC and fiber sensors since sensor response takes approximately 15 seconds to stabilize at the measuring points. The PCPP program outputs a g-code (e.g., $G01 Xx_1 Yy_1 Zz_1$) as motion control data describing the resulting path planning.

5.2.8 Fabrication of the Spherical Test Part

The hemisphere test part ($R = 20$ mm, $h = 15$ mm) was created using CAD software (Rhino 6). The hemisphere part was selected for characterization of the spatiotemporal sensing algorithm since the spherical surfaces exhibit challenging topographical features for conformal path planning [145]. The test part was fabricated using a plastic extrusion 3D printer (Mini2; LulzBot) with vendor-recommended settings. Briefly, a linear velocity of 60 mm/s, layer spacing of 0.18 mm, and gradual infill density ranging from 10% to 90% were used to fabricate the test part. Next, Pluronic F127 hydrogel and Silicone were conformally printed following a circular filled pattern using the point cloud-based path planning (PCPP) algorithm [183] across the surface of the test part with a 20-gauge tapered tip ($d = 0.6$ mm), extrusion pressure range of 8-15 psi, and printing speed of 5 mm/s. The conformal 3D printing was performed using a custom microextrusion 3D printing system, which included a three-axis robot (MPS75SL; Aerotech), a digital pressure regulator (Ultimus V; Nordson), and a motion controller (A3200; Aerotech).

5.2.9 Characterization of Test Part and Tissue Properties

The proposed methodology was applied to characterize a test part and multiple foods, including animal and plant tissue. (meat), and plant tissue (fruit). Food (meat – beef and fruit – avocado) was obtained from a local grocer and maintained at room temperature for 1 h prior to characterization. The characterization process was completed on the objects using a 3-axis robotic system with a feed rate of 1 mm/s throughout the study. Prior to freezing-thawing treatment of the food (meat) samples, the bioimpedance distribution was first characterized at room temperature. The food samples were subsequently stored at -18° C for 24 hours and then at 4° C for 24 hours. The sample was then maintained at room temperature for 1 hour prior to characterization. The total inspection time was 25 seconds per inspection point. The temporal resolution of the system is determined by the sensing tool's sampling rate and stabilization time.

5.2.10 Data Analysis and Image Processing

The sensor signals were recorded continuously during the spatiotemporal sensing process. Thus, the sensor data at the inspection points (*i.e.*, when the sensor was in contact with the object) was isolated from the sensor data in air (*i.e.*, when the sensor was traveling to the next inspection point) using the peak analyzer in Origin Pro 2021, and the average sensor response was recorded for each inspection point. The sensor response could not be recorded when the sensor failed to be in contact with the sample. Hence, the sensor response data was matched with the inspection points using the timestamps. The inspection points on the test part were next categorized as Pluronic F127 hydrogel and silicone based on the corresponding material type at that point using image analysis. Similarly, the points on the animal tissue were labeled as muscle and adipose tissue. Photographs of the tissue were acquired by using a digital camera (D7200; Nikon) from the top

view before the spatiotemporal sensing process. The photographs were analyzed using image analysis software (ImageJ; NIH) and CAD software (Rhinoceros 6). The adipose tissue was first isolated using the ‘color threshold’ command to filter the white color associated with the adipose tissue. The filtered image was then transferred to CAD software along with the inspection points to detect the corresponding tissue type. The same process was applied to the test part to isolate the Silicone material using image analysis and to categorize the inspection points.

5.2.11 Statistical Analysis

Statistical analysis was completed in Origin Pro 2021. Student’s or Welch’s t-test was used for the experiments except for the before/after freezing the animal tissue experiment where paired t-test was used. *, **, and *** indicate a p-value (p) less than 0.05, 0.01, and 0.001, respectively. The number of measuring points (n) is specified for each experiment.

5.3 Results and Discussion

5.3.1 Concept of Robotically-directed Nonplanar Tissue Property Inspection via Real-time Combinatorial Impedimetric Sensing

As shown in Figure 5.1, the automated method for characterization of bulk tissue and organ 3D spatial properties begins with nonplanar toolpath generation for the robotically-directed sensing process. A nonplanar inspection path was generated across the object (e.g., tissue) surface for each sensor (see Figure 5.1a) based on point cloud data to cover the user-defined inspection area and safety tolerance (d). Nonplanar toolpaths for tissue property inspection were generated for PEMC and fiber sensors (see Figures 5.1b and c, respectively). PEMC sensors facilitate the characterization of hydrogel viscoelastic properties via electrical impedance spectroscopy and

real-time monitoring of circuit (sensor) resonant frequency, quality factor, and phase angle across the 10 – 50 kHz frequency range [191,218,219]. Multifunctional fibers facilitate characterization of tissue bioimpedance via electrochemical impedance spectroscopy and real-time impedimetric monitoring of circuit (sensor) impedance at a fixed frequency (10 kHz) [202,217,220]. Phase angle and impedance spectrums of the PEMC and fiber sensors over the frequency range of 5 Hz - 50 kHz in air are provided in Figures 5.1d and e, respectively. An illustration of the inspection path generated by the adapted PCPP algorithm is shown in Figures 5.1f and g, which avoids potential tissue damage via tool collision. A description of the adapted PCPP algorithm for tissue inspection path generation is also provided in Figure 5.2.

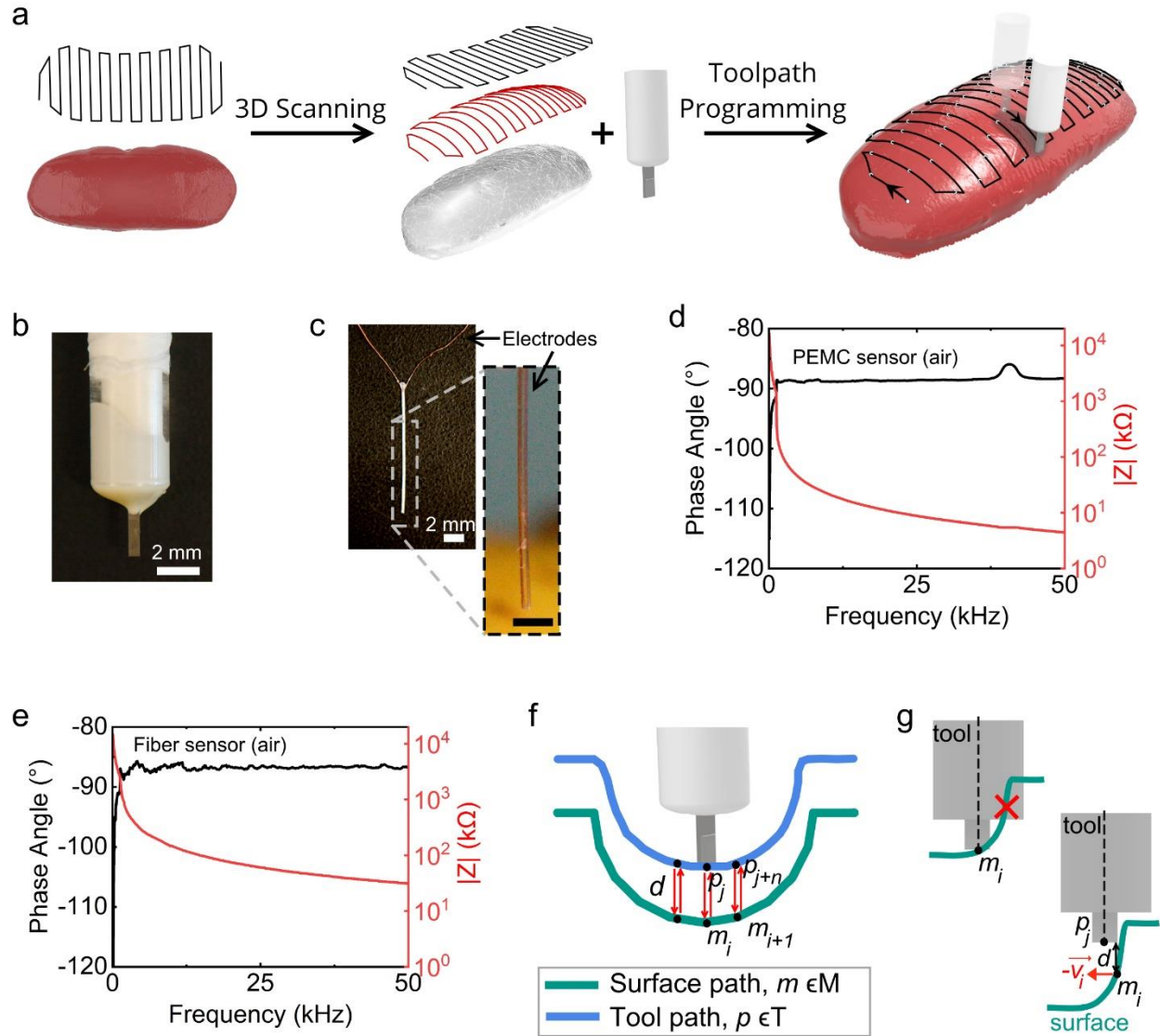


Figure 5.1 a) Illustration of the automated method for characterization of bulk tissue 3D spatial properties via nonplanar robotically-directed sensing. Photographs of the piezoelectric-excited millimeter cantilever (PEMC) **(b)** and multifunctional fiber **(c)** impedimetric sensors. Phase angle and impedance spectrum of the PEMC sensor **(d)** and the fiber sensor **(e)** over the frequency range of 5 Hz-50 kHz in air. Illustration of the nonplanar inspection path generated by the adapted PCPP nonplanar path planning algorithm **(f)** and tissue collision mitigation principle **(g)**. Scale bars = 2 mm.

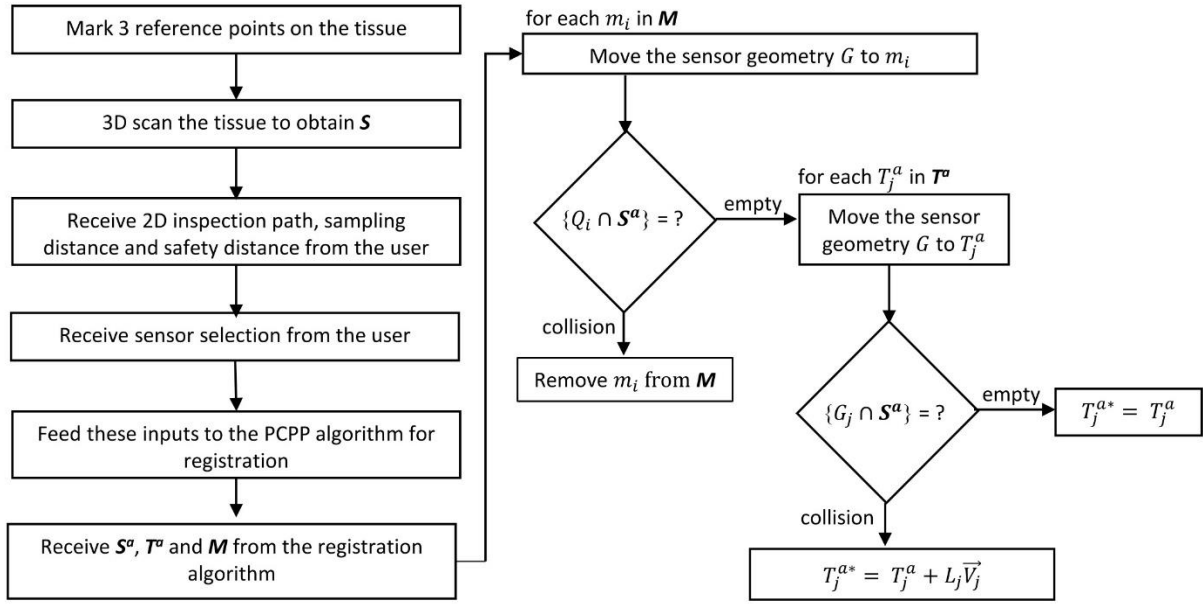


Figure 5.2 Description of the adapted PCPP program for nonplanar inspection path generation.

5.3.2 Validation of the Automated Method for Characterization of Bulk Tissue and Organ 3D Spatial Mechanical Properties using a Test Part

Having described the measurement principle, we next validated the method by characterization of 3D test parts that exhibited varying spatial distributions of tissue property. To establish a 3D test part that exhibited a distribution of mechanical properties, patterns of hydrogel and silicone were printed onto a 3D test part. The materials in the regions from the inner circle through the outer circle were hydrogel, silicone, and hydrogel, respectively (Figures 5.3a and d). The inspection path corresponding to a distance of 2 mm between adjacent inspection (i.e., measurement/characterization) points is shown in Figures 5.3b-c. Figure 5.3d shows the representative temporal PEMC sensor resonant frequency and phase angle responses for three

measurement events. The spatial distribution of the sensor response at each measurement location is obtained based on the known relationship between measurement time and tool path location. Figure 5.3e shows the 3D spatial distribution of the PEMC sensor phase angle response across the test part from a top-down perspective. Figures 5.3f and g highlight the 3D spatial distributions of the PEMC sensor phase angle and resonant frequency responses, respectively. The material type corresponding to each inspection point obtained using image analysis is also highlighted in Figure 5.3h. As shown in Figures 5.3i, the phase angle of the sensor in Pluronic F127 hydrogel ($n = 85$ inspection points) was significantly different than the phase angle in silicone ($n = 94$ inspection points) ($p < 0.001$), which has a significantly lower modulus (0.02-0.03 vs. 1.6-4.1 MPa) [221–223]. The estimated boundaries between materials are highlighted in Figure 5.3e. A comparison of the estimated boundaries with the part's 3D spatial distribution of properties is shown in Figure 5.3h. We note that while the PEMC sensor phase angle response exhibited a significant correlation with the viscoelastic properties (Figure 5.3j), the resonant frequency response did not provide a direct correlation, which is consistent with previous studies. For example, the phase angle and the frequency changed from $\phi = -85.79 \pm 0.96^\circ$ and $f = 58.63 \pm 1.56$ kHz, respectively, to $\phi = -86.42 \pm 0.82^\circ$ and $f = 58.63 \pm 1.56$ kHz as the sensor moved from contact with Pluronic F127 to silicone.

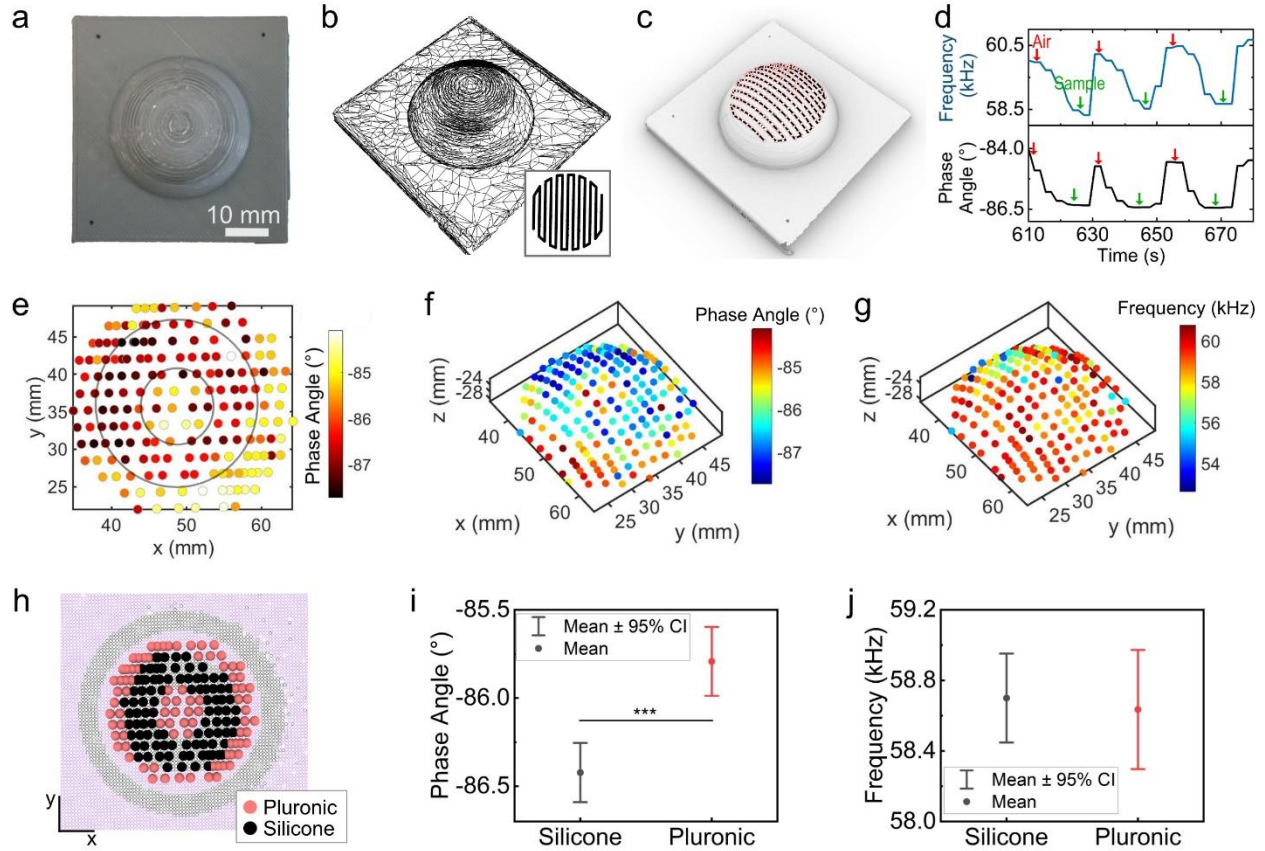


Figure 5.3 Highlight of the automated method for characterization of soft object 3D spatial properties via nonplanar robotically-directed sensing on the test part with a spherical surface. Photograph (a) and associated scanning data (b) of the object. (c) Rendered projected tool path data onto point cloud data. (d) Partial time-series data showing the observed cantilever impedance phase angle and resonant frequency as the tool travels through the measuring points collecting data in air and on the sample. (e) 2D spatial distribution of phase angle at the measuring points on the object. 3D spatial map of the phase angle (f) and the resonant frequency (g) across the object. (h) 2D map of the material types corresponding to each measuring point. Comparison of the phase angle (i) and the resonant frequency (j) of the cantilever sensor on Silicone and Pluronic F127. (***) $p < 0.001$).

5.3.3 *Automated Characterization of Muscle Tissue and Food (Meat) Quality (Adipose (Fat)-to-Muscle Tissue Distribution) via Robotically-directed Conformal Sensing using PEMC Sensors*

Having demonstrated that the method enables mapping of the non-uniform mechanical property distribution of a test part that coincided with the non-uniform distribution of hydrogel and elastomer coatings, we next applied the method for characterizing the spatial distribution of mechanical and dielectric properties of natural tissues. The composition of meat products, such as the adipose tissue (fat) ratio, is recognized as being an important quality measure since adipose tissue carries an important contribution to the taste [91,224–226]. The resulting adipose (fat)-to-muscle tissue ratio can be used as an estimator for the sensory quality of meat [91,224–226]. The tool path associated with the nonplanar inspection of the meat sample is shown in Figures 5.4a-c. The Young's modulus of adipose and muscle tissue has been previously characterized as 2-4 and 12-18 kPa, respectively [227–229]. Thus, the results associated with Figure 5.3 suggest that the method may facilitate automated characterization of the adipose tissue distribution throughout the muscle tissue. Recall, our control studies shown in Figure 5.3 show that robotically-directed sensing via PEMC sensors facilitates resolution of the 3D spatial distribution of a soft object's mechanical properties. The spatial distributions of the phase angle and the resonant frequency of the PEMC sensor across the meat are presented in Figures 5.4d-f. The estimated boundaries between the tissue contents are highlighted on the 2D property map of the meat in Figure 5.4d. Figure 5.4g shows the tissue type distribution on the inspection points. As shown in Figures 5.4h and i, the difference in the PEMC sensor phase angle on muscle and adipose tissue was not significant, while the resonant frequency on muscle ($n = 170$ inspection points) was significantly different than on adipose tissue ($n = 35$ inspection points) ($p = 0.003$) ($\phi = -87.05 \pm 0.39^\circ$ and $f =$

49.37 ± 0.54 kHz for muscle tissue vs. $\phi = -87.19 \pm 0.57^\circ$ and $f = 49.83 \pm 0.76$ kHz for adipose tissue).

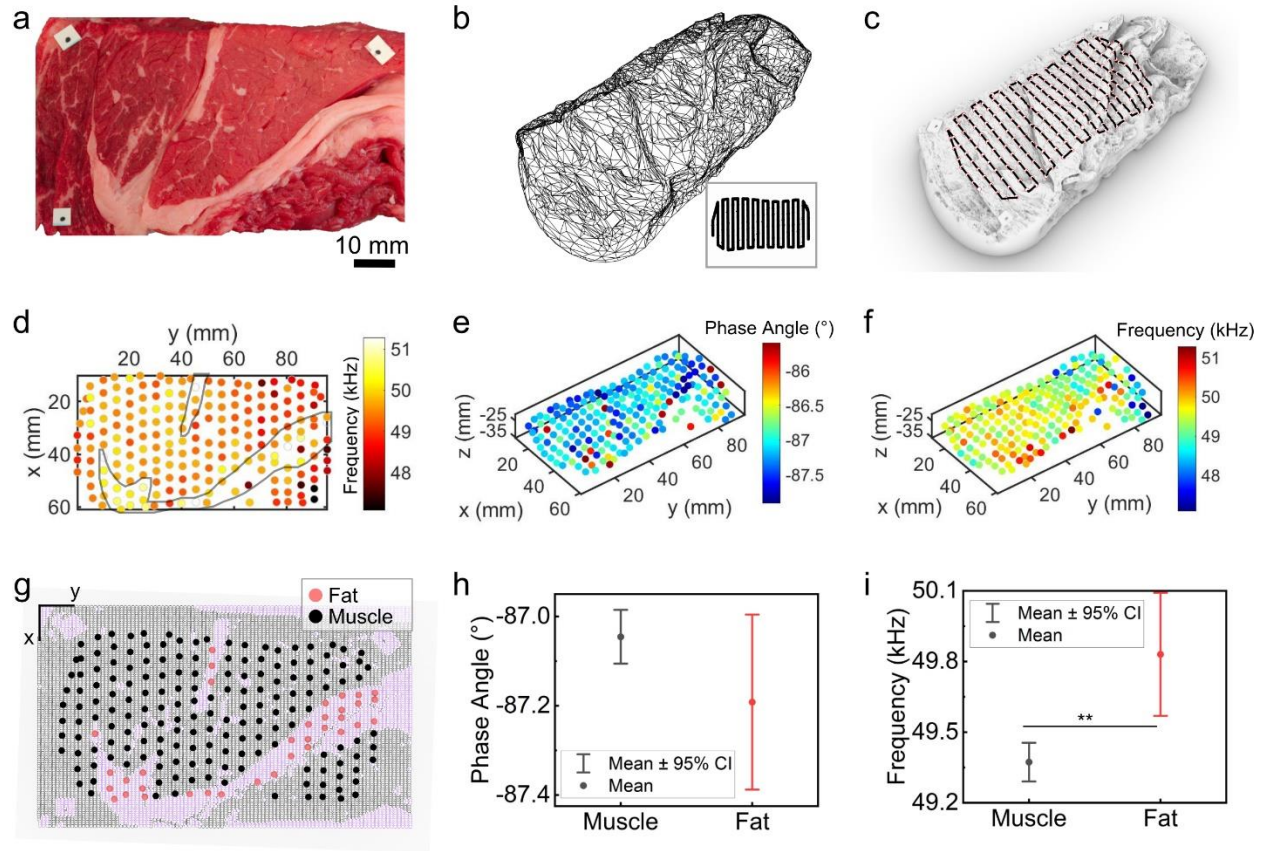


Figure 5.4 Application of the automated inspection method for characterization of meat tissue and food (meat) quality to obtain bulk tissue 3D spatial mechanical properties via nonplanar robotically-directed sensing using PEMC sensors. Photograph **(a)** and associated scanning data **(b)** of the meat. **(c)** Rendered projected tool path data onto point cloud data. **(d)** 2D spatial distribution of the resonant frequency of the cantilever sensor at the measuring points on the meat. 3D spatial map of the phase angle **(e)** and the resonant frequency **(f)** across the meat. **(g)** 2D map of the tissue types corresponding to each measuring point. Comparison of the phase angle **(h)** and the resonant frequency **(i)** of the cantilever sensor on muscle and fat tissue. (** $p < 0.01$).

5.3.4 *Automated Characterization of Plant Tissue and Food (Fruit) Quality (Ripeness) via Robotically-directed Conformal Sensing using PEMC Sensors*

Having applied the method to automated characterization of bulk muscle tissues that exhibit a variation of surface height across a 44 cm² area, we next applied the method to characterization of bulk plant tissues that exhibit increasingly complex shape. Several studies show that the changes in the mechanical properties and electrical impedance of fruits are correlated with the physiological state of the fruits such as apples, bananas, and avocados [203,230–234]. For example, bulk material properties of fruits are currently utilized for monitoring of fruit quality and provide data for real-time decision-making throughout the production chain [203,230,234]. Figures 5.5a-d show the application of the automated process for spatial tissue property inspection to characterization of fruit quality, specifically, the ripeness of avocados. Figures 5.5e and f show the spatial distribution of the PEMC sensor resonant frequency and phase angle across the unripe and ripe avocado, respectively. While the change in phase angle response between the unripe and ripe samples was insignificant, as shown in Figure 5.5g-h, the resonant frequency of the PEMC sensor on the unripe avocado ($n = 114$ inspection points; $f = 50.27 \pm 0.93$ kHz) was significantly different than on the ripe avocado ($n = 103$ inspection points; $f = 48.67 \pm 2.49$ kHz) ($p < 0.001$).

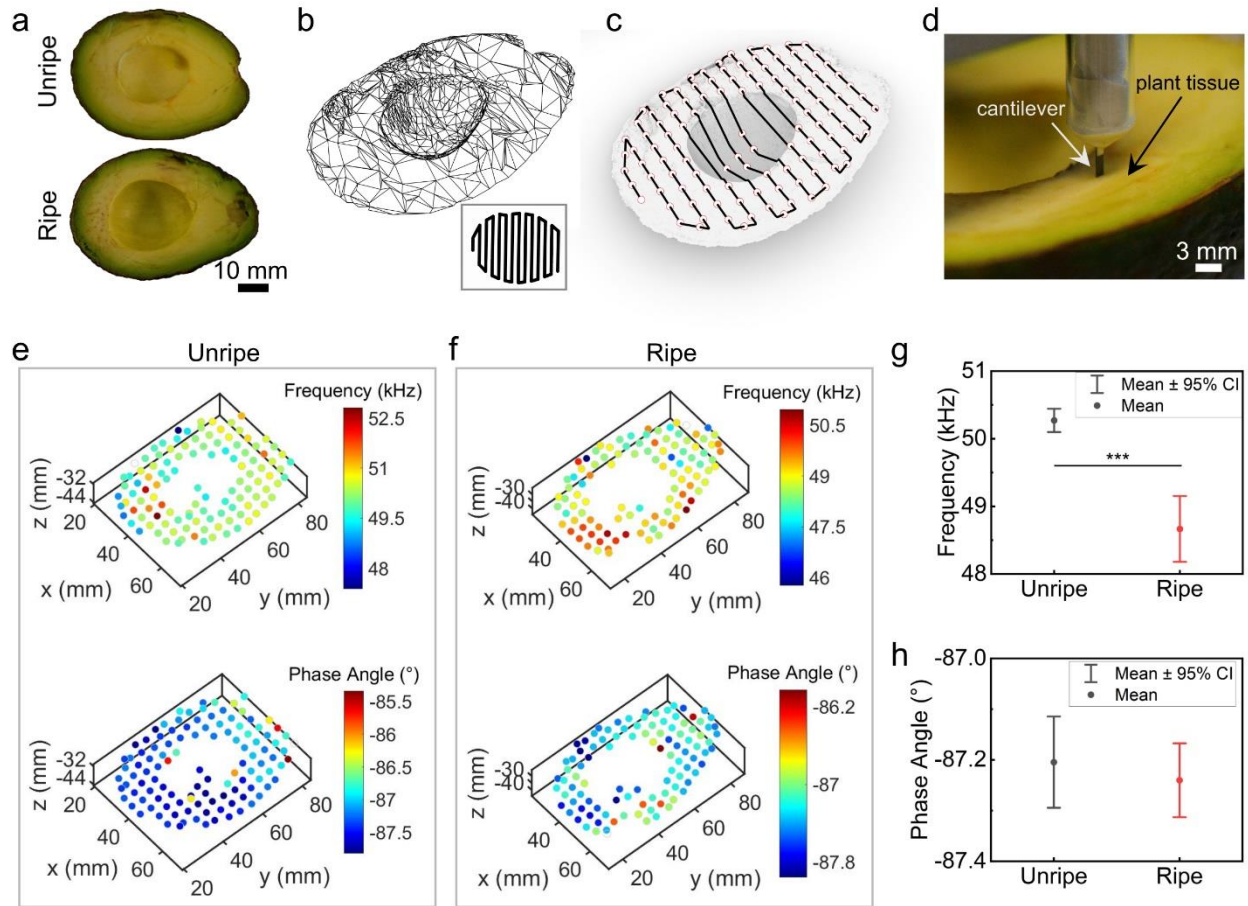


Figure 5.5 Application of the automated inspection method for characterization of plant tissue and food quality (fruit ripeness) to obtain bulk tissue 3D spatial mechanical properties via nonplanar robotically-directed sensing using PEMC sensors. Photograph (a) and associated scanning data (b) of the fruit. (c) Rendered projected tool path data onto point cloud data. (d) Photograph showing the cantilever sensor at a measuring point on the fruit during the spatiotemporal sensing process. 3D spatial map of the resonant frequency and phase angle across the unripe (e) and ripe fruit (f). Comparison of the resonant frequency (g) and the phase angle (h) of the cantilever sensor across the unripe and ripe fruit. (***) $p < 0.001$.

5.3.5 *Automated Characterization of Muscle Tissue and Food (Meat) Quality (Bioimpedance Distribution) via Robotically-directed Conformal Sensing using Multifunctional Fiber Sensors*

Having established that PEMC sensors facilitate automated characterization of bulk tissue 3D spatial mechanical properties of multiple tissue and food types, we next examined the ability to characterize additional bulk properties via alternative sensor selection, such as multifunctional fibers (see Figure 5.1). Figures 5.6a-d show application of the method to characterization of meat quality via automated mapping 3D spatial bioimpedance distribution using multifunctional fiber sensors. The electrical impedance of meat (i.e., bioimpedance) can be utilized as a freshness indicator in quality control, since freezing and thawing of meat disrupts cellular structure because of ice crystal formation [91,235]. Hence, freezing processes impact the dielectric properties of composite tissues, such as meat [206]. Bioimpedance analysis has also been used to characterize the adipose tissue (fat) composition in meat products given that the water content and dielectric properties differ in muscle and adipose tissues [91,224]. The spatial distributions of the tissue impedance (i.e., bioimpedance) at 10 kHz and phase angle based on the multifunctional fiber sensor before and after the freeze-thaw cycle are shown in Figures 5.6e and f, respectively. Figure 5.6g shows that the meat exhibited a higher bioimpedance after freezing-thawing treatment than before the freezing. The bioimpedance was significantly different on the meat before ($n = 167$ inspection points) and after ($n = 167$ inspection points) ($|Z| = 0.13 \pm 0.09 \text{ M}\Omega$ vs. $|Z| = 0.25 \pm 0.08 \text{ M}\Omega$, respectively; $p < 0.001$). The difference in phase angle before and after the temperature treatment was not significant.

Similar to the tissue type characterization using the cantilever sensor (Figure 5.3), we also examined whether the phase angle and impedance are significantly different on adipose and muscle tissue after freezing and thawing using the data shown in Figure 5.6f. Figures 5.6i and j show the top view of the meat and tissue types obtained by image processing on the inspection points, respectively. Figures 5.6k and l show 2D spatial property maps for impedance and phase angle across the meat, respectively. The estimated boundaries between the tissue types are highlighted in Figures 5.6k and l. As shown in Figures 5.6m and n, the impedance and phase angle on muscle ($n = 133$ inspection points) were significantly different than on adipose tissue ($n = 34$ inspection points) ($p < 0.001$). Specifically, the sensor exhibited an impedance and phase angle of $|Z| = 0.24 \pm 0.08 \text{ M}\Omega$ and $\phi = -63.72 \pm 19.34^\circ$, respectively, on muscle tissue, while it exhibited $|Z| = 0.30 \pm 0.07 \text{ M}\Omega$ and $\phi = -80.73 \pm 15.59^\circ$ on adipose tissue.

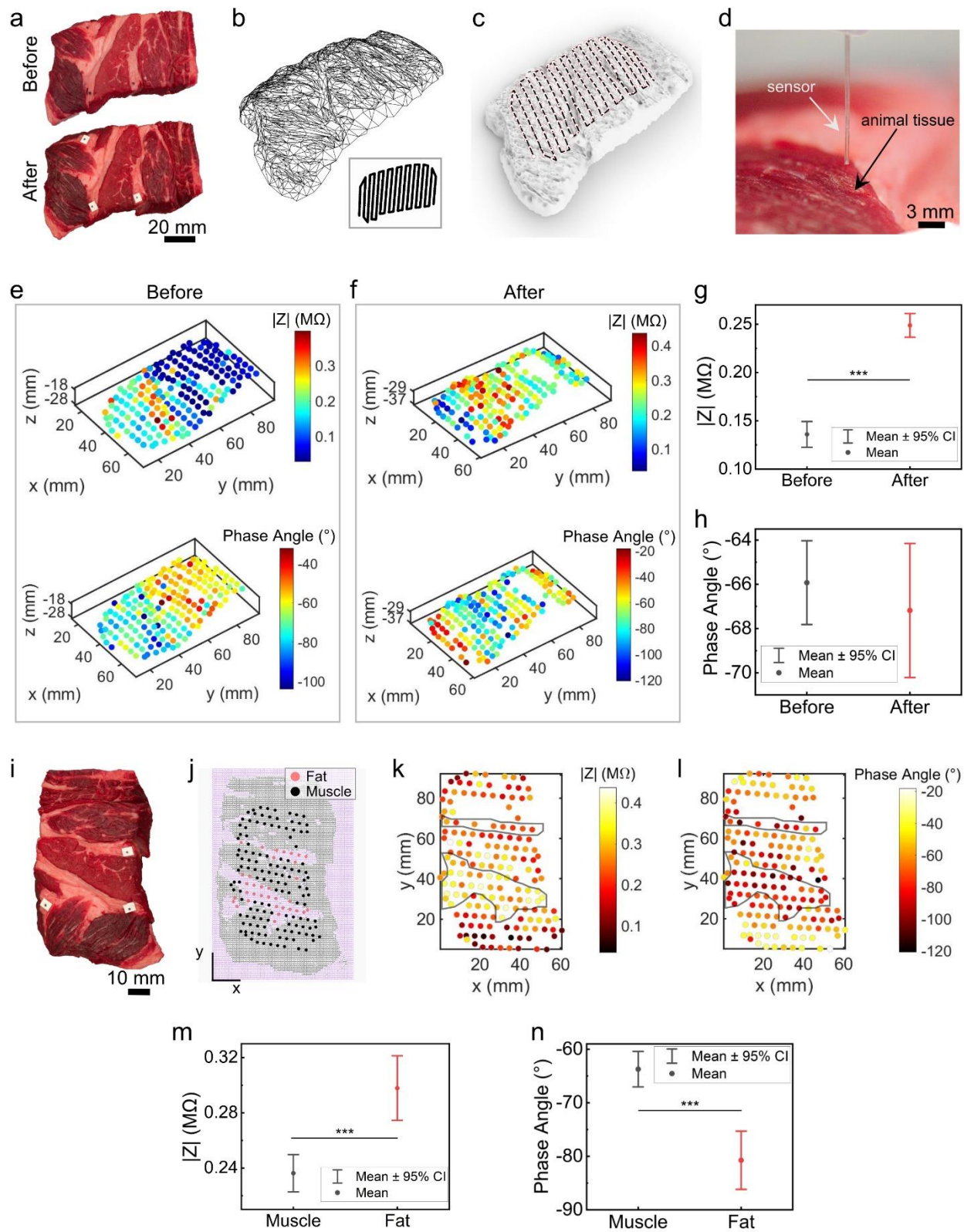


Figure 5.6 Application of the automated inspection method for characterization of meat tissue and food quality (meat freshness) to obtain bulk tissue 3D spatial mechanical properties via nonplanar robotically-directed sensing using multifunctional fiber sensors. Photograph **(a)** and associated scanning data **(b)** of the meat. **(c)** Rendered projected tool path data onto point cloud data. **(d)** Photograph showing the fiber sensor above an inspection point on the meat during the spatiotemporal sensing process. 3D spatial map of the impedance and phase angle before **(e)** and after **(f)** freezing and thawing of the meat. Comparison of the impedance **(g)** and the phase angle **(h)** of the fiber sensor across the meat before and after freezing and thawing. **(i)** Photograph of the meat. **(j)** 2D map of the tissue types corresponding to each inspection point. 2D spatial distribution of the impedance **(k)** and phase angle **(l)** of the fiber sensor at the inspection points on the meat. Comparison of the impedance **(m)** and the phase angle **(n)** of the fiber sensor on muscle and adipose tissue. (***) $p < 0.001$.

5.4 Conclusions

This work presented an automated method for characterizing the spatial distribution of material properties of nonplanar macroscale tissues. Importantly, the method facilitates automated inspection of spatial tissue quality without the need for manual or prolonged sensor-tissue integration. The utility and impact of the method was validated by application to automated inspection of food quality based on the use of multiple impedimetric sensors that facilitate monitoring complementary tissue quality attributes, including 3D spatial distribution of mechanical properties and bioimpedance. Here, we reported a novel method based on reverse engineering-driven non-planar path planning and robotically-directed sensing for automated inspection of 3D spatial material property distributions. This method is potentially useful for

automated inspection of foods and tissue-based products, such as additively manufactured implantable and consumable tissues and organs.

5.5 Supporting Information

This supporting information document contains the pseudo-codes associated with path planning algorithms.

Algorithm 6 - Registration Algorithm: Tool path alignment-projection algorithm.

Input: **S**: The mesh structure of the point cloud data that is achieved by the 3D scanner
 $[\mathbf{S}^r]_{3,3}$: Three reference points that are area centroids of the holes in the point cloud data

$[\mathbf{P}]_{3,3}$: Three reference points that are obtained by the printer controller

$[\mathbf{T}^{2D}]_{3,m}$: A list of sampled points on the i^{th} 2D path, $T^{2D}_{3,j} = 0$ for all $j = 0, \dots, m$ where $m = \lfloor L_p / 2w \rfloor$ where w is the inspection tool diameter or width.

h : Inspection distance (resolution) set by the user.

Output: $[\mathbf{T}^a]_{3,m}$: Aligned and projected path points

$\mathbf{S}^a$: Aligned mesh structure of the point cloud data

$[\mathbf{M}]_{3,n}$: Inspection point list

Initialize $\mathbf{S}^a$, $[\mathbf{T}]_{3,m}$, $[\mathbf{T}^a]_{3,m}$, $\mathbf{G}$, $\mathbf{M}$;

$\mathbf{T} \leftarrow$ Project $\mathbf{T}^{2D}$ onto $\mathbf{S}$ in z-axis direction;

Find transformation matrix $\mathbf{G}(\mathbf{S}^r, \mathbf{P})$;

$\mathbf{S}^a \leftarrow \mathbf{G}\mathbf{S}$; /*align the point cloud data to the 3D printer frame*/

$\mathbf{T}^a \leftarrow \mathbf{G}\mathbf{T}$; /*align the path points to the 3D printer frame*/

$\mathbf{M} \leftarrow$ A list of sampled points on $\mathbf{T}^a$ with a distance of h ; /*obtain inspection point list*/

Return $\mathbf{S}^a$, $\mathbf{T}^a$, $\mathbf{M}$

Algorithm 7 – PCPP Algorithm for automated inspection: Generation of collision-free inspection path planning.

Input: $[\mathbf{T}^a]_{3,m}$: 3D path points on the surface obtained by the Algorithm 1
 $[\mathbf{M}]_{3,n}$: 3D inspection points on the surface
 d : The safety distance set by the user.
 $\mathbf{S}^a$: The mesh structure of the point cloud data that is obtained by the Algorithm 1
 G : The NURBS representing the sensor geometry.
 Q : The NURBS representing the sensor holder geometry.
 L

Output: $[\mathbf{T}^{a*}]_{3,m}$: G-code points that the inspection tool will follow
 $[\mathbf{M}]_{3,n}$: Inspection point list

Initialize $c_j, q_j, L_j, M, r_j, V_j$;
for each point m_i in $\mathbf{M}$ **do** /*for each point on the surface*/
Move the bottom center of Q to m_i ;
 if there exists an intersection points list $\{Q_i \cap \mathbf{S}^a\}$ **then**
 Remove m_i from $\mathbf{M}$;
 end if
end for
for each column j in $\mathbf{T}^a$ **do** /*for each point on the surface*/
 $T_j^{a*} \leftarrow T_j^a$;
 $T_{j,z}^{a*} \leftarrow T_{j,z}^a + d$;
Move the bottom center of G to T_j^{a*} ;
 if there exists an intersection points list $\{G \cap \mathbf{S}^a\}$ **then**
 $c_j \leftarrow$ the centroid of the list $\{G \cap \mathbf{S}^a\}$;
 $q_j \leftarrow \{G \cap \overrightarrow{T_j^{a*} + MV_j}\}$; /* M is a number greater than the tool width w^* */
 $r_j \leftarrow |T_j^{a*}, q_j|$;
 $L_j \leftarrow r_j - |T_j^{a*}, c_j| + 0.1$; /*0.1 is the tolerance set by the user*/
 $V_j \leftarrow \overrightarrow{p_j, T_j^{a*}}$;
 $T_j^{a*} \leftarrow T_j^{a*} + L_j V_j$;
 end if
end for
return $\mathbf{M}, \mathbf{T}^{a*}$;

6 Conclusions and Outlook

This thesis presented research and development of three computer-aided tool path planning methodologies to improve non-planar 3D printing and biosensing capabilities on freeform surfaces. The utilities of the proposed methodologies were demonstrated by the fabrication of conformal constructs on stationary and moving substrates and by spatiotemporal sensing of food products including animal and fruit tissues. The research contributions of this thesis and future work directions are presented in this chapter.

6.1 Research contributions and conclusions

In this dissertation, three path planning methodologies were proposed to improve the conformal additive manufacturing process and inspection of biological constructs. Specifically, the main contributions of this dissertation are:

- I. *The tool path planning methodology for quality 3D printing on objects with freeform surfaces using reverse engineering (Chapter 3):* A non-planar tool path programming algorithm based on point cloud representations of object geometry was developed. The proposed methodology enabled conformal microextrusion 3D printing on objects of near-arbitrary freeform shape using user-defined 2D tool paths that have a comparable length scale to the object's radius of curvature ($L_p \gg R$). Also, this work enabled a three-axis robot to facilitate high-quality conformal microextrusion 3D printing. The utility of the novel conformal microextrusion 3D printing process was demonstrated by the fabrication of 3D spiral and Hilbert-curve loop antennas on various non-planar substrates, including wrinkled and folded Kapton films and

origami. This work provides a new method for conformal 3D printing on one-of-a-kind objects and non-planar thin substrates.

- II. *Establishing the relationship among nozzle standoff distance, surface topographical features, and 3D printing quality (Chapter 3):* A systematic study of the effect of surface features on optimal nozzle standoff distance was reported. Three standoff distance structures were compared based on the errors in filament width and thickness by conformal 3D printing on a test part that exhibited a combination of 3D topographical features with various slopes and curvatures. The nozzle standoff distance required to achieve quality conformal 3D printing was dependent on the object's position-dependent shape characteristics (*e.g.*, slope and curvature) and the tool trajectory (*i.e.*, whether the tool was ascending or descending). Corrections in the nozzle standoff distance based on position-dependent object shape and tool trajectory characteristics enabled mitigation of commonly observed conformal 3D printing defects, such as distortion of the printed material, poor adhesion to the surface, and contact between the nozzle and the surface, which are referred to as a flattening, floating, and tool-surface contact defect respectively.
- III. *Sensor feedback integration into the conformal 3D printing process in the presence of mechanical disturbance and arbitrary motion (Chapter 4):* A sensor integrated adaptive tool path planning method was developed for conformal microextrusion additive manufacturing in the presence of mechanical disturbance and substrate motion, including random vertical displacement (*i.e.*, step changes) and continuous vibration (frequency (f) = 0.2, 0.4 and 1.3 Hz, amplitude (A) = $0.8 - 6.7d$, where d is the nozzle diameter). Closed-loop controlled conformal 3D printing process enabled control of the tool position based on the feedback error in standoff

distance using a 1D laser displacement sensor and facilitated consistent material deposition on moving substrates and objects. The utility of the method was demonstrated by microextrusion additive manufacturing on planar substrates oscillating at the frequencies associated with tissue motion caused by human physiological processes, including respiration and the heartbeat. The method was also validated by *in situ* bioprinting on a human hand in the presence of random vertical motion ($A = 0 - 34.5d$). This work provides a method for planar and nonplanar additive manufacturing on moving substrates and objects of complex freeform surfaces without the need for preprocesses, such as 3D scanning and reference marker placement. Thus, the proposed methodology may potentially support various emerging additive manufacturing applications, including *in situ* bioprinting and additive manufacturing in environments that are prone to mechanical disturbance, such as vehicles, vessels, aircraft, and spacecraft.

- IV. *Spatiotemporal biosensing methodology for 3D quality mapping of tissues and organs (Chapter 5)*: A reverse engineering-driven collision-free path planning program was developed for automated inspection of macroscale biological specimens, such as tissue-based products and organs. The proposed path planning program generated custom inspection paths based on the selected inspection tool and the surface geometry of the sample. The utility of the path planning program was demonstrated by the characterization of meat and fruit tissues using two impedimetric sensing tools: a cantilever sensor and a multifunctional fiber sensor. The proposed methodology enabled the output of spatially resolved 3D property maps representing the impedimetric characteristics of the samples. Through various inspection applications on meat and fruit tissues, it has been shown that the 3D impedimetric response maps facilitated the detection of differences in tissue types, meat freshness, and fruit ripeness. This work

provides a new method for automated inspection of macroscopic tissues and organs with complex shapes.

6.2 Future Research Directions

Tool path planning is a key part of various automated (*i.e.*, robotically controlled) manufacturing and inspection processes, including extrusion-based additive manufacturing, bioprinting, machining, dimensional inspection, and biosensing. This dissertation mainly focused on extrusion-based 3D printing processes using materials that exhibit Herschel-Bulkley rheological properties, given their printability. Future studies, which incorporate rheological properties of the deposited material (*i.e.*, ink) into the tool path planning algorithm structure, may be undertaken to achieve quality conformal 3D printing of Herschel-Bulkley inks that exhibit low yield stress (*i.e.*, flow after deposition). Applications of the proposed tool planning methodologies may be extended to the robotics systems with higher degree of freedom such as 5-axis and 6-axis systems. Also, feedforward and model predictive control systems can be integrated to the path planning program to further minimize the dimensional errors in the constructs that are conformally 3D printed on moving freeform surfaces. The proposed closed-loop controlled tool path planning methodology for 3D printing onto freeform surfaces can also be applied to the automated inspection of bulk tissues, and this method may enable sensing on tissues and organs that are challenging for the 3D scanning process. Although the use of a 1D displacement laser sensor for closed-loop controlled conformal 3D printing provided a high sampling rate (1 ms), future studies may investigate new methodologies that combine sensors with high sampling rates and computer-vision systems to obtain complete information on the object's rotations and deformations. Future studies may also focus on incorporating optimization methods into the tool path planning to

minimize the total inspection process time and tool travel time. Integration of multiple sensors and artificial intelligence into the conformal 3D printing and inspection processes is also a valuable topic to be further explored.

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