# The Application of Robotic 3D Printing in Neuroprosthetic Interfaces

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**ABSTRACT**
Currently, robots can replicate artificial limbs with high precision. Various electrode implantation methods have been proposed to give users more control over prosthetic limbs, which differ in the way signals are transmitted inside and outside the body. However, the inevitable disadvantage of these methods is that they interact with the surrounding environment, resulting in decreased implant effectiveness and longevity. To overcome this problem, the application of tissue engineering in the integration of neural tissue with electrodes has been explored as an alternative source of the recording. Using hydrogel polymers as inks for 3D printing can reduce the degree of foreign body response to a certain extent. This paper reviews some representative neuroprosthetic interfacing strategies and the common disadvantages. In conjunction, this paper also investigates the applicability of 3D bioprinting in tissue engineering. By simulating the 3D printing of manipulators on complex surfaces in different ways, it can be concluded that robotic 3D printing technology can be applied in neural interface surgery and alleviate the possibility of current neural interface problems.

***Keywords:*** *3D Bioprinting, Neuroprosthetic Interfaces, Robotic Surface Tracking.*

## 1. INTRODUCTION

Losing a limb is a devastating experience that can dramatically affect the quality of life. The goal of bionic replacement technology is to replace a missing or damaged part of the human body with a fully integrated and symbiotic prosthetic limb that allows the user to feel and control the prosthetic limb as if it were a real part of the human body [1]. However, the main technical difficulty is the durability and effectiveness of establishing interfaces between these advanced robotic systems and the human nervous system. Tissue engineering is a new discipline that studies the regeneration, repair or establishment of functional tissues or organs similar to human organs [2]. With the increasing demand for organ replacement and tissue regeneration, 3D printing is considered to be an important technology in tissue engineering. Replacing traditional 3D-printed inks with bio-inks containing other biomaterials can provide additional mechanical support for bio-printed cells to help them organize, migrate and differentiate into functional tissues [4]. Thus, foreign body response caused by foreign body implantation can be further improved.

In this paper, several common strategies for designing nerve repair interfaces and current research progress of bio-ink are reviewed. The path calculation of different manipulators is simulated and their advantages and disadvantages are listed respectively. This study provides a feasible solution to the foreign body reaction frequently caused by the interface of the neural prosthesis.

## 2. NEUROPROSTHETIC INTERFACING STRATEGIES

Neuroprosthetic interfacing strategies use electrodes to connect to the nervous system and record signals, which are designed to restore function lost through spinal cord injury (SCI) [5]. Multiple signals from the body have been used to control the movement of prosthetic limbs. These methods can be broadly subdivided into the central nervous system-based control and peripheral nervous system-based control.

### *2.1. Central Nervous System (CNS) Based Control*

The brain-computer interface (BCI) is typically connected to record signals from the central nervous system to drive a prosthetic limb. Brain-computer interfaces provide a direct brain interface via invasive or non-invasive approaches [6]. As the name suggests, the invasive approach enables direct communication between the brain and a computer or another external device, which requires direct implantation into the brain during neurosurgery. Electrocorticography (ECoG) is an invasive monitoring method that uses electrodes placed directly on the exposed surface of the brain to record electrical activity in the cerebral cortex. In contrast, the non-invasive approach studies the brain in an indirect way. For example, conventional electroencephalography (EEG) is the most commonly used non-invasive approach that can monitor this activity from outside the skull (Fig. 1). Compared to ECoG, EEG is a safer way to record brain activity, but it has a poorer spatial resolution due to an information gap that does not occur directly in the cerebral cortex.

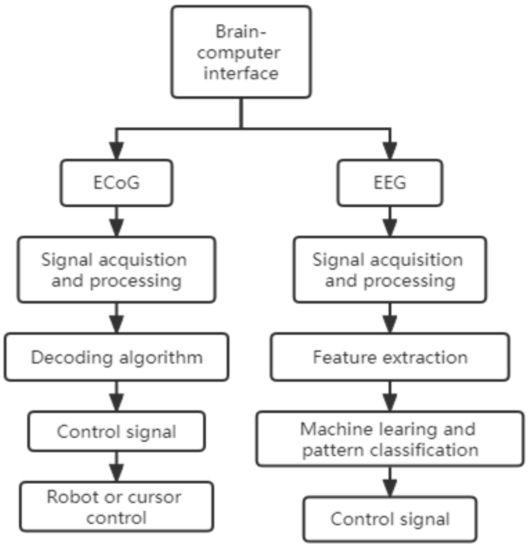


**Figure 1** Comparison of ECoG and EEG signal processing [7].

### *2.2. Peripheral Nervous System (PNS) Based Control*

Axons of sensory and motor neurons travel in and from the spinal cord forming the peripheral nerves. Different types of electrodes have been developed to connect PNS to record and/or stimulate the electrical activity of nerve fibers for different biomedical applications [8], which can be classified into three main classes depending on invasiveness damage: extraneural, intraneural, and regenerative (Fig. 2).

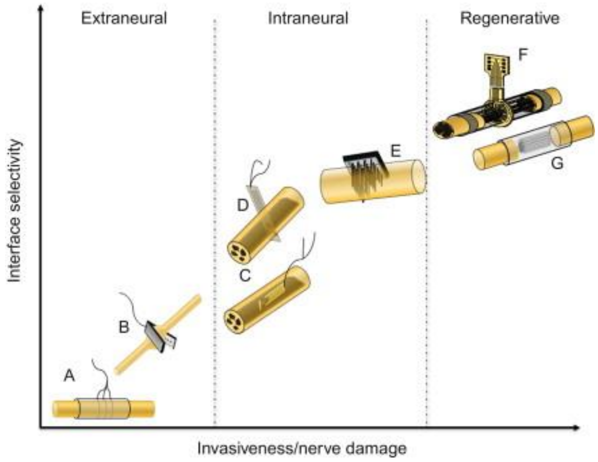


**Figure 2** The classification of peripheral nervous system based control [8].

Electrodes are classified according to invasiveness damage. As shown in figure 2, the controls numbered alphabetically refers to cuff electrode, flat interface nerve electrode (FINE), longitudinal intrafascicular electrode (LIFE), transverse intrafascicular multichannel electrode (TIME), multi-electrode array (USEA), sieve electrode and micro-channel electrode respectively.

Extraneural electrodes provide simultaneous interfaces with many axons of the nerve, resulting in poor selectivity but little nerve damage. The cuff electrode (Fig. 2A) consists of a cylindrical sheath that wraps the nerve longitudes and has two or more electrode positions in the lumen [9]. They can be precisely positioned and significantly reduce the intensity of stimulation because the cuff insulated sheath limits leakage of current from the cuff nerve space. A flat interface nerve electrode (Fig. 2B) is a variant of the cuff electrode design, which expands the cross-section of the nerve by applying a small pressure, thereby increasing its surface area. This flattening of the nerve causes the axon to move from the center to the surface, closer to the site of electrode activity [8].

Intraneural electrodes are implanted in the nerve tract, which shows better selectivity than the extraneural electrodes because they may be in closer contact with different bundles of superficial and deep nerve locations. However, better selectivity comes at the cost of higher invasiveness. A longitudinal intrafascicular electrode (Fig. 2C) is constructed by inserting thin insulated wires or polymer wires longitudinally into a single fascicular nerve so that it is positioned between and parallel to the nerve fibers [9], which provides high selectivity to interface a small population of nerve fibers within one fascicle. The transverse intrafascicular multichannel electrode (Fig. 2D) is designed similar to LIFE, with the only difference being that wires are implanted in the nerves transversely. Such a design can record or stimulate different subgroups of axons in each intramural tract on the cross-section of the nerve, thus achieving reasonable spatial selectivity [10]. Regenerative electrodes provide the highest selectivity but also the highest invasiveness damage. These electrodes do not implant whole nerves but allow nerves to grow through them.

### 2.3. Foreign Body Response

Once a medical device is implanted, its longevity and stability become critical. Both the central nervous system and the peripheral nervous system-based control are confronted with the challenge of the physiological foreign body response, which is based on non-specific protein adsorption, immune and inflammatory cells occurring under normal physiological conditions to protect the body from a foreign body.

Implantation of the device and associated tissue damage can trigger a range of inflammatory and wound-healing responses that are typical of rapid proliferation. The inflammatory response includes an initial acute phase followed by a chronic phase [11]. The acute phase is marked by fluid and protein exudation and neutrophilic reactions. Persistent inflammatory irritation, due to the presence of biomaterials or medical devices, can lead to chronic inflammation, which is usually characterized by the presence of monocytes, macrophages, and lymphocytes, as well as the proliferation of blood vessels and connective tissue to rebuild the affected area [12]. The terminal phase of the foreign-body response involves a vascular and collagenous fibrous capsule that limits the implant and prevents it from interacting with the surrounding tissue. Therefore, the in-body function and durability of any implanted device could be compromised by the body's reaction to foreign substances. Some general approaches to overcome instability in implanted devices, such as biocompatible material coatings, have been investigated.

## 3. TISSUE ENGINEERING AND 3D BIOPRINTING

Extrusion bioprinting is most frequently used among current 3D bioprinting strategies which can provide structures with high cell density in a scalable manner. Extrusion-based bioprinting involves the extrusion of bio-inks through nozzles to create three-dimensional structures [14].

### 3.1. Current Category of Bio-ink

3D bioprinting is a process of printing in a predetermined way using ink-impregnated cells based on a digitized 3D model, which allows immediate scaffold cellularization and the generation of complex structures. Finding suitable bio-inks is critical in 3D bioprinting because it provides and adapts to a tissue-specific microenvironment that can support cell growth and maturation. Hydrogel polymers have the advantage of easy mechanical and biochemical modification. At present, natural hydrogel-based bio-inks can be divided into protein-based, polysaccharide-based, dECM based and multi-component [4]. The use of cell-loaded inks offers opportunities for organ manufacturing and regeneration to enhance cell differentiation. The application of natural hydrogel bio-ink in the regeneration of damaged tissue, including embedding nerve cells into fibrin hydrogel, aims to establish a brain tissue model for neural tissue [4].

### 3.2. 3D Bioprinting on Complex Surfaces

Robotic manipulators can be used to control the position and orientation of deposition tools during bio-ink material deposition and avoid collision between the tool and the surface, which requires accurately positioning the deposition tool. According to the coordinate processing process of the manipulator, we can roughly divide it into two ways.

#### 3.2.1. Offline 3D Surface Tracking

In offline 3D surface tracking, the path points on the tool path are calculated by projecting the tool tip plane design onto the 3D scanning point cloud of the complex surface. The 3D scanning point cloud of the complex surface is obtained by the laser scanner. As the obtained coordinates are based on the position of the laser scanner, we also need to know the position of the manipulator relative to the laser scanner, and through coordinate transformation, we can get the 3D scanning point cloud coordinates of the complex surface relative to the manipulator. Note that it is necessary to obtain the distance between tool tip and flange so that we can directly use coordinates to represent the position of the tool tip rather than the flange position. After all the relative positions are obtained, the coordinates of the printed trajectory can be computed. The tool tip should be at the same distance from the surface during printing in order for the ink to be smooth and uniform in thickness.

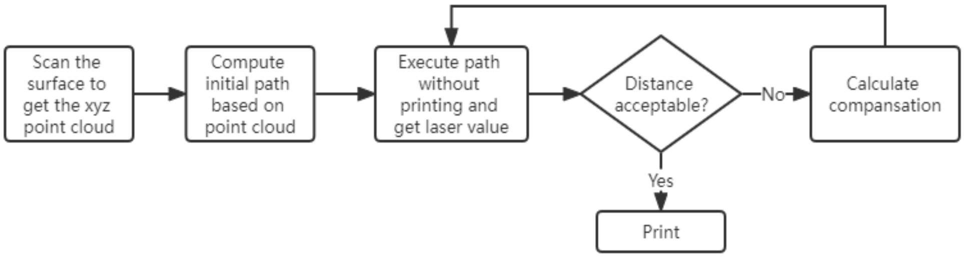


**Figure 3** Flowchart indicating the steps in the offline 3D printing process.

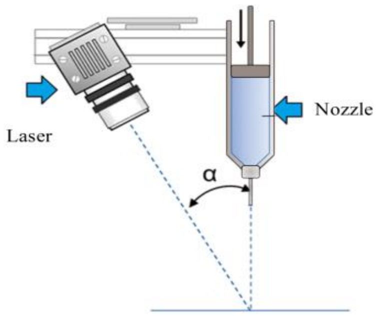


**Figure 4** Schematic illustration of the placement of the laser and nozzle**.**

After computing the initial path based on the point cloud, there is still a distance error between the tool tip and the surface when trying to drive the manipulator to deposit material. The gap error comes from many sources, including laser scanning accuracy, operation error and calculation error. Distance compensation is required to avoid the tip hitting the substrate surface and to ensure continuity of ink deposition. The portable laser scanner is a good and convenient tool to intuitively reflect the distance from the tip to the surface. In this device, both the nozzle and the portable laser scanner are fixed to a structure that is simultaneously fixed to the flange of the manipulator (Fig. 3). Hand-eye calibration is first carried out to specify that the position of the laser beam on the surface is consistent with the tip (Fig. 4). In this simulation, it is assumed that the manipulator moves vertically only along the Z-axis. The scan value of the first point is taken as the reference point, and since there is an angle between the laser and nozzle, the distance that the manipulator needs to be modified in the Z direction can be calculated according to that angle.

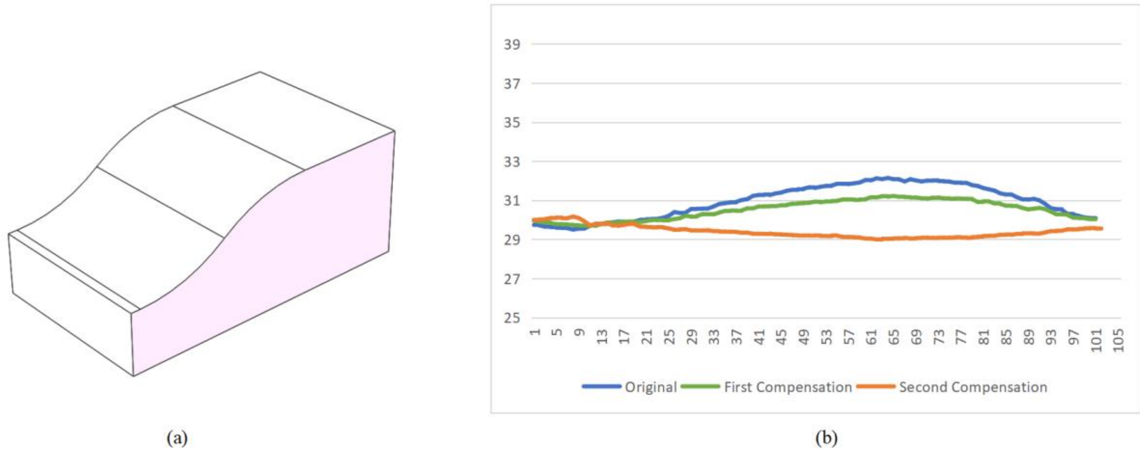


**Figure 5** (a) Complex surface for simulation (b) Gap variations along z direction when printing a circle on a complex surface.

Figure 5b shows that after compensating several times, the variations between the distances decrease from 0.85 to 0.30, which indicates the necessity of gap compensation for successful printing of the complete patterns.

The pattern printed by this method is more accurate and reduces the probability of collision between the nozzle and the working surface. However, this method still has some defects and needs further improvement. First of all, this only works with stationary objects or surfaces. Secondly, because the current setting is that the manipulator only moves in the z-axis direction and the rotation angles remain unchanged, the tool tip cannot print on the surface with a large radian or the side of the object. Therefore, in subsequent experiments, the rotation angles and change of xyz coordinates of the manipulator need to be taken into account, which involves a series of calculations.

### *3.2.2. Real Time 3D Surface Tracking*

In order to solve the problem of printing directly on deformable surfaces, a printing nozzle integrated with a laser scanner can be used as a good visual sensing system to track time-varying geometry. In this simulation, it is still assumed that the manipulator moves vertically only along the Z-axis. Due to the uncertainty of surface change, this method does not need to obtain three-dimensional point cloud coordinates of the plane at first. After getting the coordinates of the plane relative to the manipulator and computing the initial path, printing can start (Fig. 6).

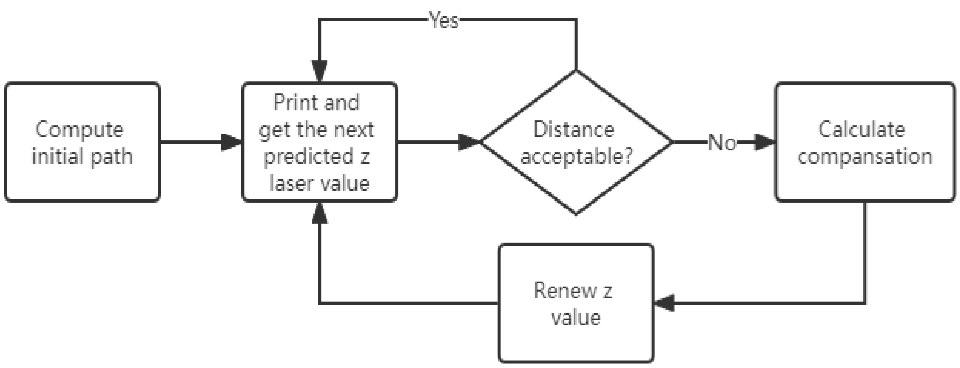


**Figure 6** Flowchart indicating the steps in the real time 3D printing process.

In the printing process, it is necessary to know the deformation degree of the next point so that the z-axis coordinates of the manipulator can be changed in real-time based on the current position. Therefore, the position of the laser beam on the surface needs to move with the tool tip, and is exactly located at the XY coordinate of the next point of the tool tip, so that the laser value of the next point can be obtained. It requires the rotation angle of the manipulator flange to change (Fig. 7) and the calculation of the manipulator height (Fig. 8).

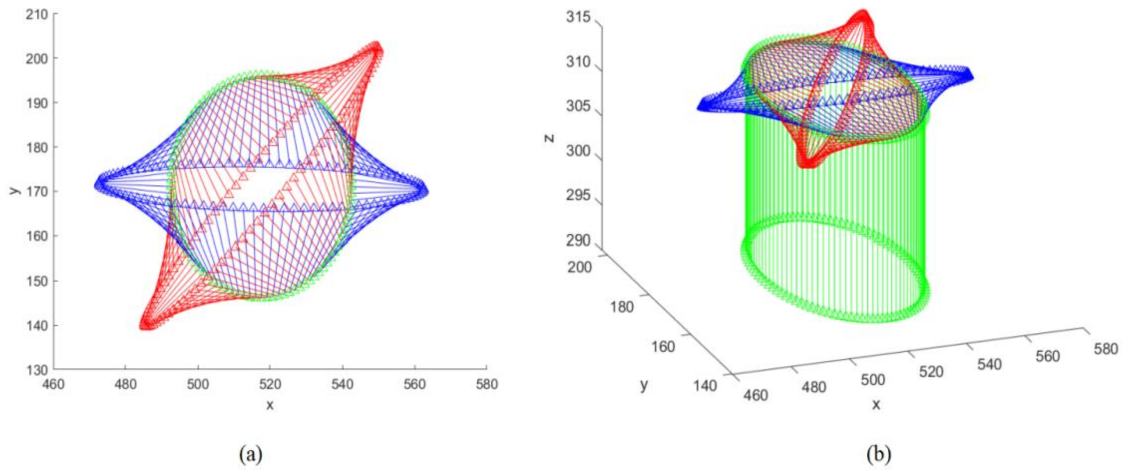


**Figure 7** TCP coordinate visualization: (a) in x-y coordinate, (b) in x-y-z coordinate.

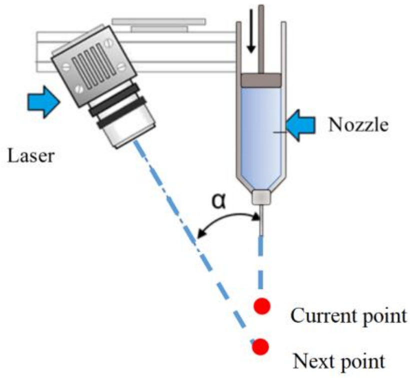


**Figure 8** Schematic illustration of predicting next point coordinate.

This method is more suitable for printing on surfaces that are prone to change, such as muscle contraction. However, this approach still has some drawbacks. First, the accuracy is not high enough to ensure that the laser beam's position on the surface is exactly the coordinate of the next point, because when the surface is deformed, the laser beam will reflect other places because of the deformation. In addition, there is a time difference between point and point positions during the movement of the manipulator, and the coordinate position determined at the previous point may change in real-time, which requires a more rigorous compensation system. Finally, this method may increase the probability of collision between the tool tip and the working surface. Due to the precision of bioprinting, the distance between the tool tip and the surface is usually at millimeter or even at micrometer level [14]. Due to time difference or calculation error during printing, The calculated z-axis coordinates of the manipulator may cause a collision between the tool tip and the surface. A stereo camera system could be used to recover the time-varying 3D geometry of the target surface in real-time [15].

## 4. CONCLUSION

With the development of advanced prosthetic technology, consumers need more intuitive user control. Whether in the central nervous system or the peripheral nervous system, direct neural interfaces have shown that intuitive control can indeed be achieved. However, the lifetime of these systems is challenged by foreign body responses. In this paper, the application of robot 3D printing on biological surfaces is discussed by simulating the trajectory of a robot arm. It can be concluded that the emergence of 3D bioprinting technology, combined with current electrode technology and robotic system, provides a basis for the interwoven fabrication of engineered tissues and interface electrodes, as well as a feasible solution to the short-lived problem of neural interface systems. This is an exciting future direction for neuroprosthetic interfaces.

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