PAM^2 system: engineering complex shaped micro-structures

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Abstract

Rapid Prototyping (RP) techniques are commonly employed for the fabrication of structure at different scale. In this work we describe a CAD/CAM based system able to process different materials in simple or complex three-dimensional shapes. The innovation of this system is the modular approach: starting from the design of the final architecture, moving to the fabrication process and concluding with the resultant properties of the material used to fabricate a structure, it is possible to control and modulate different parameters. In the emerging approach of tissue engineering and regenerative medicine, two crucial aspects for the fabrication of a scaffold are the architecture [1] and the mechanical properties [2]. Starting from these assumptions, in this work we focus our attention on the feasibility to reproduce a biological micro-environment. Using PAM^2 Graphical User Interface (GUI) complex shaped geometries were designed to fabricate the desired structures. In this work we describe the control architecture of the system and show how computational models of the extrusion phase of different materials can be used to establish working parameters for the fabrication of complex micro-structures.

Introduction

Rapid Prototyping (RP) techniques offer the potential to design and fabricate highly reproducible 3D well-shaped structures. RP is a subset of mechanical processing techniques which allows the realisation of highly complex and reproducible structures. The 3D structures are fabricated one layer at a time via computer-aided design (CAD) models and computer-controlled tooling processes (CAM). RP methodologies use specific polymers and materials designed specifically to meet the processing requirements of each RP system. The first technique developed with this concept was Fused Deposition Modelling (FDM) developed by Hutmacher et al. [3]. Other techniques have been developed in this direction using a pressurised syringe to produce scaffolds with complex geometries and a wider range of processing capabilities [4, 5]. The PAM system [6] was one of the first systems developed in this direction. However, the transfer of RP technologies to encompass biocompatible and bioresorbable materials still poses a significant challenge, particularly in developing 3D scaffolds for tissue engineering applications. Merging all these requirements we developed and patented [7] a modular micro-fabrication system purposely designed to handle and dispense a multitude of materials with different processing technologies. Using the modular approach different techniques and materials can be processed and controlled at the same time. PAM^2 is an evolving and adaptable system and can fabricate milli- or centi-meter scaled 3D scaffolds. A Graphical User Interface (GUI) is used to design simple or complex shaped 3D structures. To control the final dimensions a Finite-Element Model (FEM) was used to describe the extrusion phase. These models were used to optimise the fabrication parameters, obtaining high fidelity complex micro-structures with controlled shapes.

PAM^2 micro-fabrication system

PAM^2 system is RP technique composed of micro-positioning three-dimensional stages (XYZ) and several processing modulus as shown in figure 1. The micro-positioning system has a spatial resolution of 1 µm, and can be controlled both in velocity and in acceleration (up to 15 mm/s). A purposely designed control software was developed to monitor all the processing parameters in real-time.

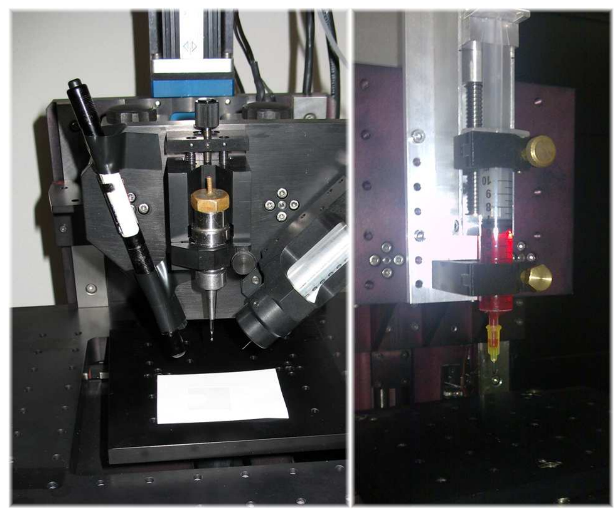

***Figure 1**. PAM^2 system: a) contemporary use of different fabrication techniques; b) piston module (PAM2)*

PAM^2 software

The software is composed of several viewlets to control each parameter of the fabrication technique (e.g. pressure, force, temperature) and the motion of the mechanical stages. A GUI module was developed to design the architecture of the fabricated structure. The innovation of the PAM^2 GUI viewlet is the feasibility of designing simple or complex patterns [figure 2a], as well as its ability to recognize specific trajectories from an anatomic tissue image [figure 2b].

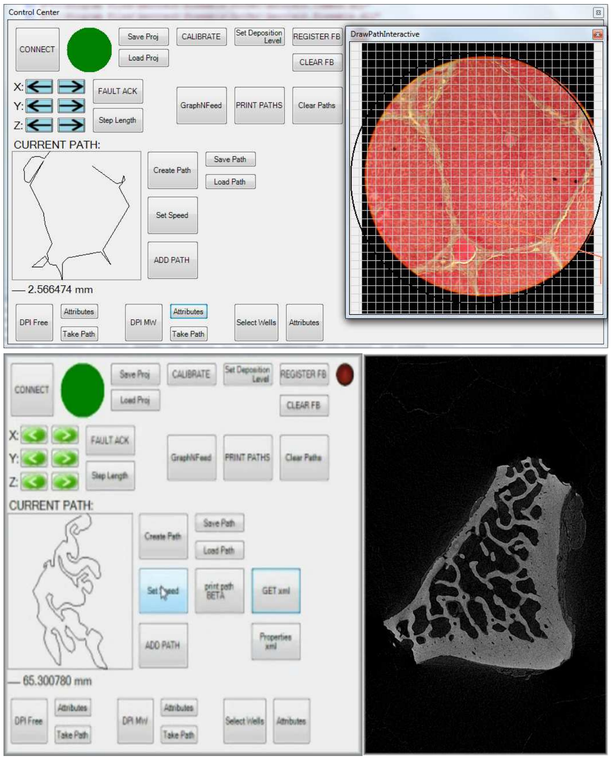

***Figure 2**. Examples of design structure architectures with PAM^2 software: a) using the Graphical User Interface viewlet to reproduce a hepatic-like path; b) trajectories obtained from the reconstruction of a bone micro-CT*

PAM^2 modular fabrication techniques

Different techniques can be used to fabricate micro-structures. In the PAM^2 system compressed air can be used as pneumatic force to extrude viscous solutions. A controlled electro valve (ITV 2030, SMC Corporation) can exert pressure in a range of 35-500 cBar (resolution of 1 cBar) and extrude low viscosity synthetic polymers solution (1-10 cP) [6], or natural polymers viscous solution [8]. To process highly viscous or solid-like solutions a piston module was inserted. A stepper motor is used to actuate a sterile and commercial syringe, allowing the extrusion of highly viscous (e.g. alginate solution, wax) or gelled materials (e.g. gelatin, collagen). This device is also used to realise bio-active scaffolds with cell suspensions [9]. Another module controls the temperature of the reservoir and of the deposition plane. Specifically the reservoirs can be heated in a temperature range of 25-70°C, while the deposition surface can be refrigerated or heated (ΔT= ±40°C respect to room temperature).

Finite-Element modelling of the extrusion phase

It is known that material extrusion is a critical fabrication phase for RP techniques. Particularly in the field of micro-fabrication it is important to predict the line width (LW) of the deposited material in order to fabricate high fidelity well-shaped and spatially controlled structures. In this work we modelled the fabrication process taking into account three important parameters involved: the generation of a drop on the needle, the material outflow and the interaction between the material and the moving deposition plane. Comsol Multiphysics software was used to simulate the extrusion phases. Navier-Stokes equations [equation 1] were combined with phase-field equations [equation 2] to track material boundaries.

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)-\nabla\cdot\left(\mu\left(\nabla\mathbf{u}+\nabla\mathbf{u}^{T}\right)\right)+\nabla p=\mathbf{F}_{st} \qquad (1)$$

$$(\nabla\cdot\mathbf{u})=0$$

$$\frac{\partial\phi}{\partial t}+\mathbf{u}\cdot\nabla\phi=\nabla\cdot\frac{\gamma\lambda}{\varepsilon^{2}}\nabla\psi \qquad (2)$$

$$\psi=-\nabla\cdot\varepsilon^{2}\nabla\phi+\left(\phi^{2}-1\right)\phi$$

Once the initial conditions were imposed and the material started to exit from the needle, different velocities of the deposition plate were investigated to predict the optimal condition to control the LW [figure 3]. For thermal-dependent materials heat transfer equations were included in the model [equation 3]. The processing of different materials was evaluated with this approach, and the final LW was eventually predicted.

$$\nabla\cdot\left(-k\nabla T\right)=Q-\rho C_{p}u\cdot\nabla T \qquad (3)$$

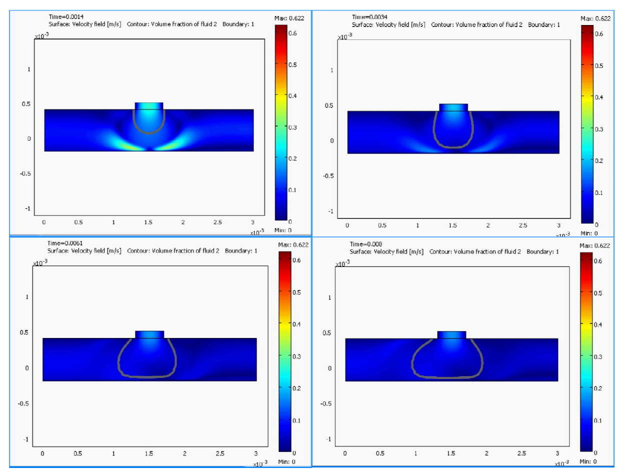

***Figure 3**. Interaction between a drop and a moving plane of deposition (velocity of 4.5 mm/s). Figure highlights the boundary of the drop of a viscous solution (viscosity and surface tension values of alginate 6% w/w) through a needle (diameter of 165 µm), exerted pressure 400 mmHg.*

Conclusions

In this work we describe the engineering of different aspects of a modular RP system for fabrication of micro-structures. A modular micro-fabrication system was developed and designed at the University of Pisa. A software control interface allows the user to design simple or complex 3D patterns, which are used to represent the final architecture of a structure. Then the micro-positioning system is controlled with all the fabrication techniques in real-time. Different materials can be processed to realise well-defined and spatially controlled 3D micro-structures. In order to improve the quality of the structures a FEM approach was used to evaluate the relationship between the working parameters during the extrusion phase. This approach is particularly useful to predict and control the fidelity and LW of fabricated micro-structures.

References

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Author Biography

Annalisa Tirella is a PhD student in Materials for Environment and Energy at the University of Rome "Tor Vergata". She is working on the design of a micro-fabrication system able to reproduce the complexity of biological environments. She is also interested in material properties (i.e. natural and synthetic polymers), and in materials able to form a well shaped hydrogel with controlled mechanical properties, suitable for tissue engineering applications.

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Giovanni Vozzi received his Laurea Degree in Electronic Engineering at the University of Pisa in 1998 and the Ph.D. in Bioengineering at the Politecnico di Milano, Italy in 2002.He is currently a researcher at Interdepartmental Center of Research "E. Piaggio", Faculty of Engineering of University of Pisa, Italy. His research interests concern microfabrication systems, in particular the realization of polymeric structures for application in Tissue Engineering, in actuation and sensors and development of organic transistors.

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