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Mesh segmentation with connecting parts for 3D object prototyping

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Abstract:
Using 3D printers for manufacturing objects has become an easy, low cost process in a variety of emerging applications, such as assistive technologies. To this end, it may be necessary to split the object in smaller parts, providing that they precisely connect. This work presents a framework to build objects with connecting parts, which is divided in main three steps: 3D reconstruction; mesh segmentation; and 3D printing. The framework includes a new method for 3D model segmentation, which allows the generation of connecting parts from cutting planes. The segmentation process uses a binary space partitioning tree to represent cut regions of the mesh obtained from the scanned object. To close these cut regions and, at the same time, to consider constraints defined by the added connectors, it is used a Constrained Delaunay Triangulation. Thus, it is guaranteed a set of closed meshes for 3D printing. Experimental results show the application of this framework in two different areas: assistive technologies, by creating anatomically adjustable orthoses; and cultural heritage, where parts of scanned sculptures can be printed for preservation and restoration activities.

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1. Introduction

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MESH SEGMENTATION WITH CONNECTING PARTS FOR 3D OBJECT PROTOTYPING

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ABSTRACT

Using 3D printers for manufacturing objects has become an easy, low cost process in a variety of emerging applications, such as assistive technologies. To this end, it may be necessary to split the object in smaller parts, providing that they precisely connect. This work presents a framework to build objects with connecting parts, which is divided in main three steps: 3D reconstruction; mesh segmentation; and 3D printing. The framework includes a new method for 3D model segmentation, which allows the generation of connecting parts from cutting planes. The segmentation process uses a binary space partitioning tree to represent cut regions of the mesh obtained from the scanned object. To close these cut regions and, at the same time, to consider constraints defined by the added connectors, it is used a Constrained Delaunay Triangulation. Thus, it is guaranteed a set of closed meshes for 3D printing. Experimental results show the application of this framework in two different areas: assistive technologies, by creating anatomically adjustable orthoses; and cultural heritage, where parts of scanned sculptures can be printed for preservation and restoration activities.

Index Terms— 3D scanning, 3D reconstruction, mesh segmentation, 3D printing.

1. INTRODUCTION

3D printing has become an attractive resource for tasks demanding reliable, low cost, and easy to use prototyping objects. In this context, 3D copies of the human body surfaces can be generated, allowing the customization of complex parts. Thus, 3D applications for assistive technologies, such as building anatomically adjusted orthoses, are growing [1, 2, 3].

Another up-to-date application for 3D printing is the digital preservation of cultural heritage. After the 3D model of an artwork is built, a decision may be needed to choose how to divide and print a 3D copy of a specific part of the object. For instance, this can be used to allow the evaluation of damages and to simulate restoration processes.

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One major challenge for applying customized 3D printing in large scale for different objects is to have reliable, automatically built 3D models. The evolution of both the 3D scanners and algorithms for 3D reconstruction has simplified this task [4, 5]. In assistive technologies, 3D scanners are being used as an important tool to obtain precise 3D reconstruction of human body parts. In this context, once the task of building segmented parts of 3D models from 3D scanners has been automated, the 3D printing of objects became feasible. However, obtaining 3D models with connected parts requires further effort [6, 7, 8]. For instance, a broken arm can be immobilized by attaching anatomically matched components in one hollow structure, which can be easily done by printing connecting parts of the 3D model of the limb.

Generating adaptable 3D components is difficult and laborious. Also, low-cost orthoses are usually generic, having the disadvantage of not being fully adaptable. This way some patients prefer do not use the orthoses. Therefore, the main contribution of this work is a complete framework to build 3D models with connected parts, which is based on cutting planes from scanned objects. Experimental results show adaptable prototypes of orthoses and segmented parts for sculptures restoration.

This paper is organized as follows: Section 2 reviews related work on our approach. Section 3 presents the proposed framework. Section 4 shows experimental results using our approach. Finally, Section 5 provides conclusions and future directions for our work.

2. RELATED WORK

Mesh segmentation has been widely studied; see [9] for a complete survey. Traditional methods cut the mesh by edges of triangles using partitioning measures. Yun *et al.* [10] proposed a robust scheme for mesh partitioning. Their method firstly segments a mesh into a set of independent connected components, then each component is further segmented into independent pieces based on the coding error rate. Shapira *et al.* [11] presented a mesh partitioning method by using a shape diameter function. Stelldinger and Bähnisch [12] proposed a method to segment meshes using boundary indicator functions, which combine color and curvature proper-

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ties. Kalogerakis *et al.* [13] presented a segmentation method where an objective function is formulated and learned from a collection of labeled training meshes. A disadvantage of these segmentation methods by edges of triangles is the creation of arbitrary segmented regions, which could generate complex connecting parts to be automated.

In addition, methods that incorporate mesh segmentation ideas for manufacturing objects have been recently proposed. Luo *et al.* [6] presented a framework for partitioning 3D models into 3D-printable parts. The 3D model is initially segmented using cutting planes, and then it is manually assembled from printed parts. Results using cutting planes show the feasibility of this method to segment 3D models and automatically create connected parts.

Other similar methods [7, 8, 14, 15] have also been proposed focusing on building articulated solid models. Bächer *et al.* [7] built articulated animated objects by using a model based on mobile joints. Calì *et al.* [8] printed articulated models and automatically assembled them with joints that exhibit internal friction. Zhou *et al.* [14] added to articulate models the possibility of being transformed into a cube or a box, using a continuous folding sequence. Jacobson *et al.* [15] proposed a tangible and modular input device for character articulation. Methods [7, 8] created some generic models of human arms and hands, however these approaches could be focused on adaptable prototyping of medical treatment devices. In this context, a complete framework of 3D reconstruction, mesh segmentation and 3D printing would generate customizable functional models to be used as orthoses and other prototypes with connected parts.

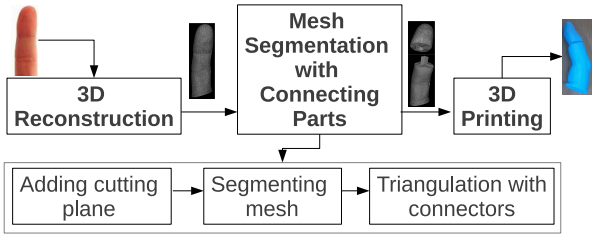

Fig. 1. Proposed framework.

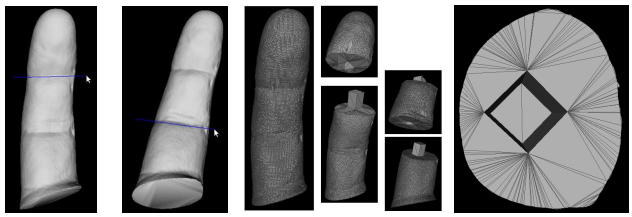

Fig. 2. Segmentation of a 3D model (finger) in parts with connectors. (a-b) The user defines the position of cutting planes (blue segments). (c) Segmented regions together with connectors are represented by a BSP tree. (d) 2D Constrained Delaunay Triangulation (CDT) generated from cutting plane in (a), new edges produced by cutting of the mesh (exterior polygon in (d)) and edges of connector polygonal base (quadrilateral on cutting area in (d)) define CDT constraints.

3. FRAMEWORK

The proposed framework starts with the acquisition of 3D images (different views from one object) by a 3D scanner. Then, the reconstruction process generates a triangular mesh, which is used as input to the segmentation with connecting parts (see [4] for details of a complete 3D reconstruction system). The segmentation method determines cutting planes through a 3D user graphical interface (GUI). By using these cutting planes, the segmentation process cuts triangles of the mesh. Then, the cutting area with the constraints defined by polygonal bases of added connectors is triangulated and, thus, segmented mesh regions are closed. Finally, closed regions are printed as connecting parts, ending a cycle of the framework (Fig. 1). The core of the proposed framework is the segmentation process with connecting parts, which will be detailed below.

3.1. Mesh segmentation with connecting parts

At this stage, the mesh is segmented in regions with connecting parts by using cutting planes as shown in Figs. 2(a-c). The method generates a connector from a polygonal base and each connector is associated to one of the two types: male or female. Fig. 2(c) shows male and female connectors with a quadrilateral base. To represent regions produced by the segmentation, the BSP (Binary Space Partitioning) is generated. This spatial structure creates a binary tree, recursively, where nodes contain mesh regions segmented by cutting planes. Thus, each node of the BSP tree stores current region triangles, and its children nodes store triangles of both the front and back of the current cutting plane, where the front is the positive side of the cutting plane defined by the direction of the normal vector. Fig. 2(c) shows a BSP tree of three levels for the segmented finger model.

The segmentation process starts with both the list of triangles of a mesh oriented counterclockwise and the list of cutting planes. Then, mesh triangles are added to the root node of the BSP tree and pointers to $front$ and $back$ children nodes are initialized to $null$. For each cutting plane, the segmentation process adds the plane by the recursive traversal of the BSP tree (Algorithm 1), then segments the current region with the cutting plane (Algorithm 2), and finally triangulates the cutting area and generates connectors (Algorithm 3). These points will be detailed below.

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3.1.1. Determination of cutting plane

Each cutting plane is determined from two clicked points (see GUI in Figs. 2(a-b)) and the displacement of these points along rays projected orthogonally to the current view. Clicked points make flexible the cutting planes determination and, thus, these generate a customized creation of the segmented model. Additionally, the direction of the plane normal vector is calculated by the input sequence of points clicked by the user.

The use of a cutting plane allows automatically generation of connectors with planar base. However, as alternative for complex connectors with non-planar base, one can use mesh segmentation by edges of triangles [11, 13].

3.1.2. Triangulation of cutting area

A 2D Constrained Delaunay Triangulation (CDT) [16, 17] is used to triangulate the polygon created by cut edges and constraints defined by the list of polygonal bases of connectors (see Fig. 2(d)). The purpose of the CDT is to ensure that segmented regions are closed in order to be correctly printed (a closed mesh is a usual requirement of 3D printing systems). Furthermore, the segmentation process ensures that segmented regions are also oriented, creating each triangle with the normal vector direction pointing to outside the region.

3.1.3. Generation of connectors

Connectors positions are defined by clicking points on the mesh using the GUI. Each connector is classified as male or female and has a polygonal base. Then, each connector is generated by using a template (a mesh of triangles with local coordinates). Thus, the connector is adjusted on the polygonal base, that is, template vertices are positioned on the polygonal base and transformed to global coordinates.

Algorithm 1 Adding cutting plane

procedure ADDCUTTINGPLANE(N, P) ▷ N : BSP node, P : plane
  if $(N \rightarrow front = null)$ & $(N \rightarrow back = null)$ **then**
    Add P to N;
    SEGMENT(N, P);
  else
    ADDCUTTINGPLANE($N \rightarrow front, P$);
    ADDCUTTINGPLANE($N \rightarrow back, P$);

3.1.4. 3D printing

Since the triangulation method ensures that each connected part is a closed and oriented mesh, then these models can be

Algorithm 2 Mesh Segmentation

procedure SEGMENT(N, P) ▷ N : BSP node, P : plane
  for each triangle T of N **do**
    if T is intersected by P in segment AB **then**
      Calculate a list Lt of new triangles produced by triangulation from vertices of T and intersection segment AB;
      Store cutting points (ends of segment AB) in a list Lp;
      for each triangle t of Lt **do**
        if t is in positive side of P **then**
          Add t to node $front$ of N;
        else
          Add t to node $back$;
    else
      if T is in positive side of P **then**
        Add T to node $front$ of N;
      else
        Add T to node $back$;
  TRIANGULATE(N, P, Lp);

Algorithm 3 Triangulation and generation of connectors

procedure TRIANGULATE(N, P, Lp)▷ N : BSP node, P : plane, Lp : list of cutting 3D points
Sort list Lp and create a polygon $Poly3$;
Transform $Poly3$ to a 2D polygon $Poly2$ by rotating vertices of $Poly3$ from the plane P to a coordinate plane, for example, to the XY-plane and eliminate the z-coordinate;
Obtain the list of positions of connectors;
For each connector position, create a polygonal base using a radius R defined by user and store the polygon in a list $Lpoly2$;
Generate a 2D Constrained Delaunay Triangulation CDT using vertices of polygon $Poly2$ and of each polygon of $Lpoly2$ with constraints defined by edges of these polygons;
Transform 2D vertices of triangles generated by CDT to 3D using the inverse rotation from the used coordinate plane to the plane P;
Add each 3D rotated triangle to the node $front$ of N with vertices in counterclockwise and to the node $back$ of N in clockwise;
For each connector, retrieve template (a triangle mesh) and adjust it on the respective polygonal base of $Lpoly2$; then add each triangle of the connector to the node $front$ of N with vertices in counterclockwise (male connector) and to the node $back$ of N in clockwise (female connector);

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correctly printed. Parts with connectors can be printed by retrieving each leaf node of the BSP tree from the triangles list. To this end, it is necessary to traverse the BSP tree (similarly to Algorithm 1) and to store triangles lists in a standard 3D printing file format such as STL (STereoLithography).

4. RESULTS

Experimental results were obtained by using 3D models generated by a reconstruction system for the Microsoft Kinect Sensor [18]. The segmentation method was assisted by the Constrained Delaunay Triangulation of CGAL (Computational Geometry Algorithms Library). GUI was implemented using OpenGL (Open Graphics Library). For 3D printing, it was used an Up Plus 2 3D printer with PLA (Polylactic Acid) and ABS (Acrylonitrile Butadiene Styrene) printing materials.

For 3D printing tests, sizes of male and female connectors must be slightly different to achieve a suitable friction. This value is difficult to define automatically since it depends on factors such as printing material type, printer precision, printing angle, among others. In experimental results, a reasonable generic friction was obtained using a radius R for the female connector polygonal base and $0.95R$ for the male one.

For assistive technologies, it was generated an initial orthosis prototype for wrist fracture (Fig. 3). A hollow model for the scanned wrist was created to cover the fractured area, so the patient can easily insert the prototype. To this end, the mesh generated by the scanner is previously cut to obtain the interest area. Then, the hollow model is created by adding an exterior mesh to the current one. The exterior mesh is generated by duplicating vertices of the current mesh and displacing them to the exterior according to the direction of smoothed normal vectors. This displacement is an user-defined thickness parameter. For this model, it was used a value of $3R$. Finally, the hollow model is partitioned by using the segmentation method with connectors, and connected parts are printed and tested. While the presented orthosis is a simple prototype, one can see the potential usefulness and ease of creation for any user by using the proposed framework.

Another important area for applying the proposed approach is the cultural heritage preservation. A sculpture made with materials sensitive to deterioration can suffer huge losses in its original shape, specially those exposed on public areas. A case study is the deterioration of The Prophets (a set of sculptures created by the artist Antônio Francisco Lisboa, known as *O Aleijadinho* [19]). These sculptures have lost areas in some critical parts such as fingers and feet, for instance, the broken left foot of the sculpture of prophet Hosea. For a restoration study of this prophet, it was created a foot prototype connected to the scaled scanned sculpture (Fig. 4). The new foot was created from the reflection of the other one. Furthermore, the prototype could be used as a cast for the fabrication of a foot with the original sculpture materials.

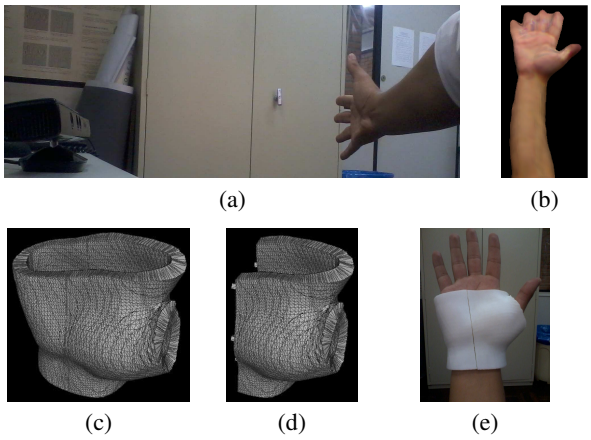

Fig. 3. Generation of an initial orthosis prototype to immobilize a wrist fracture. (a) 3D scanning, (b) reconstructed arm model adapted to anatomic shape of the user, (c) the model is cut to obtain the interest surface and then a hollow model is created to put in the wrist, (d) the mesh is segmented by one cutting plane and connectors are generated to join parts, and (e) finally, the prototype is printed in ABS and put on the wrist.

Fig. 4. Scaled restoration of left foot of the prophet Hosea (left sculpture) compared to the original scanned model (right sculpture). Models were printed in PLA.

5. CONCLUSIONS AND FUTURE WORK

It was proposed a framework for prototyping objects from the segmentation of a model in connecting parts. Results show the simplicity to create preliminary, user-defined connected models. Although the presented prototypes should still be refined to generate precise final models, the potential use and quick creation of these models by any user is feasible using the framework presented here. In the future, it is planned to improve the development of prototypes for assistive technologies, with the participation of patients and specialists from our University Hospital. Also, we will try to adapt new prototypes to the human body by testing new adjustable connectors.

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