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Contour Matching in Image-based CAD using B-splines and Digital Geometry

David Durón-Arellano[1], Mehran Mehrandezh[2]
[1]University of Regina (Canada)
[2]Faculty of Engineering and Applied Science, University of Regina (Canada)
[1]duad92@gmail.com, [2]mehran.mehrandezh@uregina.ca

Abstract
Recent developments on generating organized Point-Clouds from sequential images taken by cameras is giving the CAD/CAM/CAE practice a quantum leap. One application domain that has gained significant amount of attention is the practice of the fast and precise production of the ergonomic objects for users with the utmost comfort level. This has been paved by the exponential advancement in the computers processing power, and the development of the new algorithms for classifying and merging a huge amount of sequential data in form of organized point-clouds. This is becoming a textbook problem rather than merely a lab curiosity. The main focus of this paper is to explain the automation process on: (1) generating a dense organized point-cloud from sequential images taken by an RGB-D camera, (2) extracting contour lines on the surfaces of interest using the concepts borrowed from digital geometry, and (3) using the information obtained in (2) to construct the objects with seamless ergonomic fit via 3D printing. Some examples are: manufacturing customized gloves, shoes, garments, etc. However, the main focus of this work is on building eye-drop medicine dispenser holders that can be customized for users through a fast, non-intrusive, and semi-automated process. This paper provides a framework on a semi-automated approach for extracting the contours of interest from a digitized CAD model obtained from a point-cloud generated through RGB-D imaging. A 3D model of the subject, i.e., a human face, is first constructed via a mesh using an RGB-D imaging sensor, called structure sensor. The radius of curvature around the scanned eye socket is then calculated along the surface normals on the point-cloud in its vicinity. The points of high deflection, i.e., points corresponding to a sudden change in the radius of curvature, are then used to determine the optimal location of the control points for B-spline fitting. The B-splined contour curve is used as the extrusion base of the eye-drop dispenser holder CAD model. This process can expand to manufacturing of devices such as: eye goggles, wrist bands, shoes, gloves, etc. We plan to incorporate the entire process to a lab module in our CAD/CAM/CAE course which includes all the steps from conception of a design to manufacturing it.

1. Introduction
When speaking of new technologies for CAD modeling, rapid prototyping, and custom products, contour matching becomes a key research topic. Nowadays the processes to manufacture products specifically designed to fit human body parts are complex and expensive. These processes involve the construction of physical models that are very time-consuming and they use very expensive materials that often can't be recycled. Thus, image-based CAD modeling and 3D printing provides an advantageous alternative.
Currently the most relevant studies on image-based CAD are on architectural planning and archaeological reconstructions [1], in dentistry with computer-guided template-based implant placements [13], manufacturing of patient-specific craniofacial biomaterial scaffolds [4], and even robot navigation [5].
In order to build a product that would assemble specific elements fittingly, a reliable model of the element's contour lines/surfaces would be needed. Therefore it is necessary to devise a systematic method that takes into account the minimum number of control variables while ensuring a good contour matching. This practice brings out the notion of digital geometry and curve fitting.
Curve fitting is widely used in data analysis and statistics [7, 8, 10]. The most relevant applications are for business to forecast future sales; for computer science, and more general curve fitting for teaching and

research use. Therefore, there was a huge body of literature that could be access upon for our application.

This paper provides a semi-automated approach for extracting the contour lines and surfaces of interest from images of the 3D objects using the concepts borrowed from the Digital Geometry. The variation of the local curvature in the digitized 3D curves, as the contour lines of the 3D objects, is used to determine the optimal location of the control (or knot) points in B-splines. B-splines are further used to approximate the contour lines on the object. These data can be used for 3D printing purposes when it comes to the manufacturing of matching parts such as eye goggles, wrist bands, shoes, gloves, etc.

We present a case study where we digitally extract the contour lines of the orbital cavity of a person from a point-cloud and use that to build a device to hold an eye-drop medicine dispenser right above the eye. In order to achieve the best ergonomic match between the drop-medicine holder and the eye-socket, we do a generalization of the eye-socket shape and we use concepts of maximums and minimums in local curvatures to find the best location of the knot points for the B-spline fitting [10]. After obtaining the knot points we use the B-splines concept to approximate the contour lines. This is further used as the extrusion base for constructing a CAD model of a final product.

We also analyze the accuracy of the contour matching process between the eye-socket and the eye-drop dispenser holder through the deviation between the contour to be matched and the generated contour. We show that a CAD model can be built in real time with an error bounded to a maximum of 4 mm.

Results show that the contour matching based on image-based CAD modeling represents a very useful method to speed up, simplify and automate the manufacturing of products that are required to be specific to the ergonomic needs of a user.

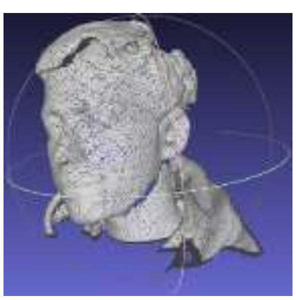
2. Selection of the Knot Point for B-spline Fitting of Body Contours

We've selected the case study of the design of an eye-drop medicine dispenser holder as something that turns to be getting more difficult to use as the people lose their motor skills. We designed a CAD model of a very simple mechanism that fits into the contour of the orbital cavity of a person's eye-socket, thus guaranteeing the proper application of the drops. Proper selection of the knot points via a B-splines curve fitting technique presents a very good method for contour matching. After manually selecting the knot points from the digitized contour lines, the CAD model is automatically reshaped fitting the person's eye-socket.

2.1 Image-based CAD

We evaluated several software packages and devices such as 123D catch, Microsoft Kinect and the structure sensor for generating a point-cloud of the objects of interest. Finally we decided to use the Structure Sensor for its ease of use, portability, acceptable accuracy and resolution, and processing time.

a)



b)

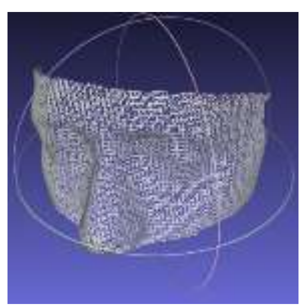


Fig. 1 Visualization of the reconstructions of the object in *Meshlab* a) complete reconstruction of the face through the structure sensor with 109000 surface patches b) Isolation of the part of the eyes after cropping, proper scaling and closing open ends.

This device uses the structured light method, in which an infrared laser projector casts a pattern towards the object. The produced image is then captured with a low resolution camera [2]. The software provided by the Structure Sensor generates a triangular mesh representation of the scanned object. *Meshlab software* was used in the next step to isolate the specific parts of the scanned object for further processing. *Meshlab* provides useful functions such as rotating, cropping, scaling, and exporting the

mesh file in object (i.e., .obj) and in point-clouds (i.e., .xyz) formats. Figure 1a and 1b show a visualization of a scanned face using the structure sensor.
After isolating the eye-socket from the scanned surface, as seen in Figure 2, we selected the exact points of the eye-socket contour and fit a 3D curve to that using B-splines. To have a reliable reference we've considered the nose pointing towards z+, centered in x = 0 with the left eye in x+, and the lowest point located at y = 0. Since the reconstruction is not proportionate in x+ (left eye) and x-(right side) we relocated the points on each side according to the location of the reference point.

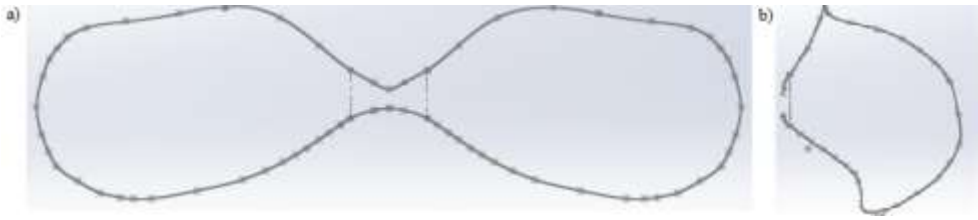


Fig. 2 Contour of the orbital cavity isolated and processed from the structure sensor's reconstruction. a) Frontal view of the contour b) Lateral view of the contour.

2.2 Contour Matching

Because of the complex topology of the eye-socket and the variation on the position of the snapshots taken, a manual determination of locations of the knot points for B-spline fitting became necessary. To speed up the process of contour matching, one would need to minimize the number of the knot points needed to construct the B-splined curve. The method suggested by Park [10] was adopted, whereas the smoothness and accuracy of the B-spline fitted curve would depend on the proper selection of the so-called dominant points to position the B-spline knots on. Several characterizations can be used as dominant points. These include local curvature maximum (LCM), inflection points and sharp bends in curvature [3]. In this case study we used a feature in the SolidWorks CAD software. It draws perpendicular lines along the 3D curves where the length of each line is proportional to the angle of curvature. The sharper the angle the larger the length, see Figure 3.

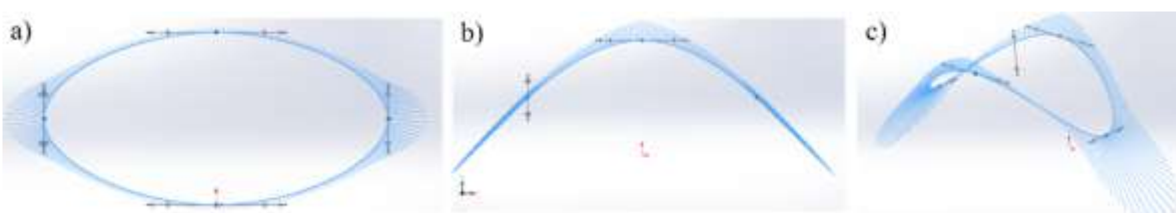


Fig. 3 Location of local curvature in oval with ends sunken towards –z a) superior view showing LCMs in the left-right ends b) lateral view showing the local curvatures and LCMs on the top c) isometric view of the oval and its curvatures.

In the process, to guarantee that the generated splines follow these knots, a control polygon with a set of control points is generated. This control polygon draws the B-splines with weighted and directionized tangent lines making them non-uniform rational B-splines (NURBS), which is an extension of the B-splines used in the CAD software, [11,6]. Similar to a polynomial interpolation a B-spline uses a series of Bézier curves, bounded in the convex hull of the control points, for curve fitting while reducing the Runge's error of oscillation. [14]
NURBS control points determine the shape of the curve. Each point of the curve is computed by taking a weighted sum of a number of control points [12]. When using the weighted and directionized tangent lines the curves are described by eq. (1) [11]:

$$C(u) = \sum_{i=1}^{k} R_{i,n}(u)P_i \quad (1)$$

Where $(P_0, P_1, \dots, P_n)$ are control points and $R_{i,n}(u)$are the rational basis functions as shown in eq. (2):

$$R_{i,j}(u,v) = \frac{N_{i,n}(u)w_i}{\sum_{j=1}^{k} N_{j,n}(u)\,w_j} \quad (2)$$

The $N_{i,n}(u)w_i$ term in the rational basis function denotes the points related to the control points. $N_{i,0}(u)$ are piecewise constant functions, $N_{i,n}(u)$ is a linear interpolation of $N_{i,n-1}(u)$ and $N_{i+1,n-1}(u)$ and w_i are the corresponding weights.

2.3 Results

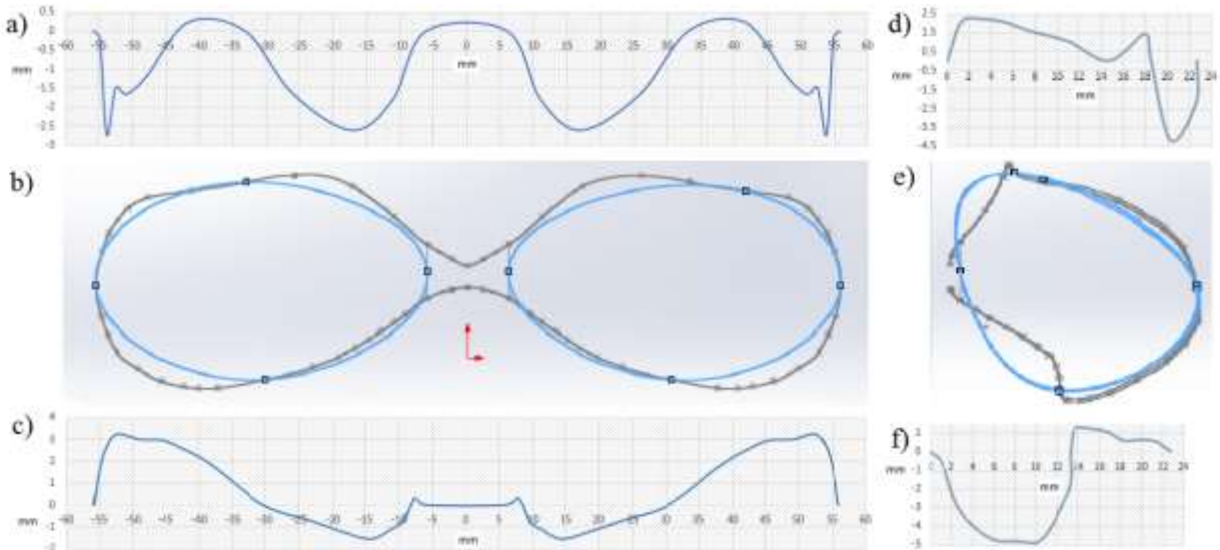


Fig. 4 Visualization of deviation between generated contour from B-splines and contour to be matched. a) Deviation in mm in the upper side, frontal view, "y" axis b) frontal view c) Deviation in mm in the lower side, frontal view, "y" axis d) Deviation in mm in the upper side, lateral view, "y" axis e) lateral view f) Deviation in mm in the lower side, lateral view

Figure 4 depicts the difference between the eye-socket contour generated by B-splines and the exact contour extracted from the point-cloud. As can be seen, the variation is higher in the areas where the curvature is furthest from the knot points. The largest difference was measured at 3-4 mm. As the number of knot points were increased this error was reduced to about 1-2 mm. However, the cost associated with the selection of a larger number of knot points is the computation time. Nevertheless since the knot points are to be manually selected following the digitized contour, the best way to guarantee the lowest variation between samples is to use the fewest number of points possible.

Eight knot points proved to be sufficient (i.e., yielding a positional error of less than 3-4 mm in all 3 directions) for the eye-socket contour matching application. The CAD model is quickly rebuilt after each selection and the user is provided with the overall accuracy through quantitative measures (i.e., the sum of the squares of point-wise positional errors). Figure 5 show a representative snap shot of the eye-drop dispenser holder CAD model.

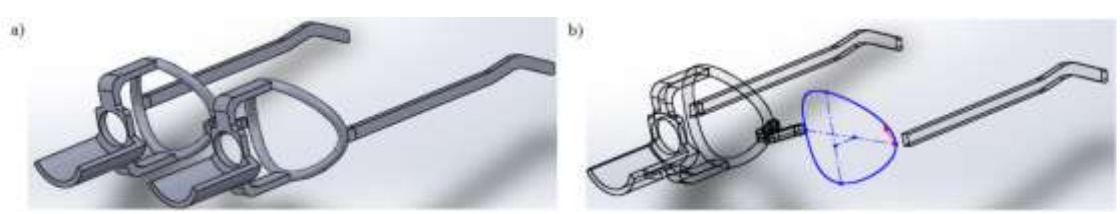


Fig. 5 CAD model of the eye-drop mechanism guided by 4 knots in each side. a) Final extrusion of the mechanism b) Highlighted blue oval as the shape base for final extrusion.

4. Concluding remarks

We have proposed a new approach for contour matching in image—based CAD through methods of digital geometry and b-spline concepts. Using the method of selecting dominant points using an image-based CAD as a series of points to customize a CAD model is simplified. This method has been found to be very useful to minimize the variables involved and the deviation between samples.
The points of the contour are isolated and its local curvature maximums are located in order to find the dominant points. These dominant points are used as knots for the B-splines and the accuracy for contour matching is shown to be a good quality approximation. As expected the bigger variations are presented in the furthest places from the knots.
For this case study the shape is very complex to be identified, therefore the knots are selected manually. Following the statement proposed, four points are the minimum but sufficient to reliably match the contour. With this method real customized products can be easily manufactured through rapid prototyping. Further improvements to automate the location of the knots in any surface may be started from surface and axis detection from current research works such as the automatic detection of the principal axes of given shapes with known symmetry properties [16] and chrominance models for the color segmentation and subsequent detection of human faces in two-dimensional static images [15]. Further improvement also aims to more complex applications such as prosthetics and medical applications.

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