Adaptive re-parameterization based on arbitrary scalar fields for shape optimization and surface fitting

Ivo Marinić-Kragić *, Milan Ćurković, Damir Vučina

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Group for Numerical Modeling and Computer Application, Postal address: R. Boskovica 32, 21000 Split, Croatia

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ABSTRACT

This paper presents a method for re-parameterization based on an arbitrary scalar field named the relaxation field. The relaxation field is applied to re-distribute the control-points of a parametric surface towards the desired areas. The proposed method was developed for possible application in an intelligent shape optimization procedure where a sensitivity field with respect to an objective function (or some other physical field) would be used for constructing the relaxation field. It could hence contribute to the concentrating the control-points at areas where significant changes in the geometry are expected. The method can easily be used in shape optimization since it keeps the number of variables constant during the redistribution of control-points as opposed to adaptive insertion of control points when using T-spline and similar methods.

The same method can also be used in surface fitting by choosing the relaxation field based on the geometric error. This leads to an adaptive iterative fitting method. The method was validated by fitting a single patch B-spline surface to triangulated point clouds. The point-clouds were obtained by 3D scanning or from a CAD model. Examples include several complex engineering objects. The proposed method uses a parameterization method based on a combination of harmonic mapping and a mapping method based on a spring mesh. By relaxation using a spring mesh, the method allocates more parametric space to the regions of interest, thus assigning them more control points. The combination of these two mapping methods provides for increased local control while keeping the global smoothness of the parameterization.

1. Introduction

Reverse engineering (Várady et al., 1997) is a process in which a CAD model is constructed from a physical part that already exists. The reverse engineering process always contains two steps. The first step is digitizing the part which is usually conducted by 3D scanning of the surface of the object. The result is an unstructured point-cloud which is typically converted to a triangulated surface mesh. In the second step, the measured points are used as input for a surface fitting procedure and the result is a compact CAD surface model.

Following these steps, a shape optimization procedure can be conducted which is often the final step of an enhanced reverse engineering process. The adaptive re-parameterization method proposed in this paper has several possible applications in these areas.

1.1. Surface fitting

Surface fitting is an important topic in computer-aided design and there is abundant literature (Weiss et al., 2002) dealing with it. Surface fitting techniques can be divided into those that do not and those that do require parameterization (assigning parameters u, v to 3D point-cloud points). The parameterization problem can be omitted by the active contour model (Pottmann et al., 2002; Pottmann and Leopoldseder, 2003) which is often used for fitting B-spline and NURBS surfaces (Saini et al., 2015). Another approach is to use iterative procedures (Lin, 2004; Kineri et al., 2012; Deng and Lin, 2014) which can also be applied to improve the computational efficiency. Still, this approach requires an initial guess which must be computed by another method. The second group of the fitting procedures require parameterization and these are the main topic of this paper.
Abundant work exists related to methods for parameterization of organized points (Floater, 1997) as well as for unorganized points (Floater and Reimers, 2001). These methods are important in many areas of science and engineering such as repairing CAD models, image processing (Yao et al., 2004) and texture mapping. Nevertheless, the most important applications for this paper are surface fitting and shape optimization, both part of reverse engineering. The first step of a reverse engineering process is the digitalization of a part. This is conducted by 3D scanning and typically results in point-clouds organized in the form of triangulated surface meshes. Various methods exist for parameterization of the triangulated meshes (mapping to a planar domain) and they almost always introduce distortions in angles and areas. Mapping methods usually minimize these or other kinds of distortions. Harmonic maps (Remacle et al., 2010) are frequently used since their approximation can be computed easily, which is usually conducted by finite element or finite difference methods. Furthermore, harmonic maps are guaranteed to be one-to-one for convex regions. Harmonic mapping in a general case is not conformal (does not preserve angles) but it does minimize deformation in the sense of minimizing the Dirichlet energy. These properties make harmonic mapping popular but various other methods are also used. In Greiner and Hormann (1997) and Becker (2011) a method based on elastic springs is used for parameterization. This method normally introduces more distortions but it is computationally efficient and easy to implement. In current paper, a method for an iterative re-parameterization based on a combination of harmonic mapping and the elastic springs mesh was developed. A parameterization method named the feature sensitive parameterization with a similar approach was developed in Lai et al. (2006). The feature sensitive parameterization method conducts the parameterization by using an area-preserving mapping and virtually increasing the area of the geometric regions of interest. As will be demonstrated later, in some cases this method produces very good results, but the method developed in this paper has several properties that are favorable in shape optimization.

Once the point-cloud parameterization is completed, the respective fitting procedure can be conducted. In this paper, B-splines are selected as parametric surfaces for fitting to the projected point-cloud. Specialized fitting techniques exist for a specific type of parametric curve or surface. For example, when fitting B-splines, special attention is needed for the distribution of knots. Free knots are long known to improve the fitting results (Schoenberg and Whitney, 1988; Jupp, 1978; Lyche and Merken, 1987) and this is still a common research topic (examples of recent papers include Kang et al., 2015; Zhang et al., 2016). Some of fitting methods were developed mainly for improving the computational efficiency of B-spline fitting (Norouzzadeh Ravari and Taghirad, 2016). With NURBS fitting (Dimitrov and Golparvar-Fard, 2014; Brujic et al., 2011) each control point weight can be an additional variable. Specialized methods were also developed for fitting T-splines (Wang and Zheng, 2013) and similar parametric surfaces such as the THB-spline (Kiss et al., 2014). Since this paper aims at developing a re-parameterization method, different fitting methods can be used in combination with the proposed method. Regarding the fitting method, a simple linear fitting method was selected in this paper and only the control points of the spline surface were fitted while the knots were kept constant. This allows for better insight into the benefits and possible problems with the proposed method.

The developed method might also be relevant to applications of reverse engineering in other research areas such as architecture (Bartoš et al., 2014) or CNC machining (Bo et al., 2016) to name a few. In addition to surface, volumetric parameterizations are also becoming important (Xu et al., 2014; Chan et al., 2017). Parts of the methods developed here for B-spline surfaces could be used for volumetric B-splines.

1.2. Shape optimization with parametric surfaces

Shape optimization is an important topic in both structural (Kociecki and Adeli, 2015; Cheng and Cao, 2014) and aerodynamic (Qu et al., 2017) shape optimization and the application of parametric surfaces is rather efficient in 3D shape optimization (Milas et al., 2014; Vućina et al., 2015; Marinić-Kragić et al., 2016b, a, 2018). This is closely related and usually follows the reverse engineering process mentioned earlier. These shape optimization procedures are usually computationally very expensive and any improvement is valuable. For example, in the paper Ćurković et al. (2017) a method for an enhanced non-linear fitting is proposed as a tool that can support a shape optimization procedure. This paper advocated using a single-patch NURBS for obtaining an initial solution in a shape optimization procedure. This could potentially accelerate the overall optimization time. The current paper has the same objective: developing a method that can be used to accelerate a shape optimization procedure.

The method developed in the current paper can be used for re-parameterization based on any scalar field called the relaxation field. In the case of fitting applications, the re-parameterization uses the geometrical error from the previous iteration to construct the relaxation field. The relaxation field is used to correspondingly expand the regions in the parameter space. Thus, more control points are allocated to the troublesome areas while at the same time being removed from simple geometric regions which do not require much modeling freedom. This effect is also very useful for (re-)modeling the parametric shape in shape optimization procedures. For fitting, the geometrical error from the previous iteration was used. In the case of shape optimization any other scalar-fields such as acting forces or design sensitivity (Allaire, 2015) with respect to an objective function could be employed. In this way, a change of geometry could be predicted and the parametric surface used in the optimization procedure could automatically cluster the points at the required area.

Smoothness and the degree of control-points redistribution can be controlled by combining the spring-mesh method with the harmonic mapping. Gradual control-point redistribution is important in shape optimization since the exact locations where the clustering will be needed is not known in advance. Alternatively, one could use a method with an ability to adaptively add control points (for example T-spline or chained Bezier surfaces Vucina et al., 2012). Nevertheless, such methods have several problems if used in shape optimization procedure. First, the number of optimization variables would change during the optimization. Second, if the control points were initially added at locations where they are not needed, an additional algorithm for removing the control points is needed. These problems could also cause premature convergence to a local optimum. Nevertheless, methods such as T-splines could be used once a near-global optimum solution is obtained by a more stable method, such as the one proposed in this paper.

2. Point-cloud parameterization for surface fitting

A point-cloud can be defined as a set of p individual points PC. A method for assigning the parameter values (u, v) to all PC, points is called point-cloud parameterization and it is obtained by mapping the 3D point-cloud to a 2D parameter space. A wide variety of methods exist for this kind of mapping and this section explains the methods used in this paper. First an elementary 1D mapping case is shown. Next, the elastic spring mesh method is explained by generalization from 1D case to 2D case, and finally the harmonic mapping method is briefly explained. After the mapping is completed, the point-cloud can be represented by a continuous function F(u, v) as described later in this section. Finally, a method for fitting a parametric surface S(u, v) to the functionally determined point-cloud F(u, v) is described.

This section also includes a short description of a similar parameterization method (Lai et al., 2006). This method will be used for
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