Advanced Mesh Repairing

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Abstract

This paper is devoted to the problem of the repairing incomplete reconstructed (damaged) CAD-models. It proposes a general concept of an abstract field whose force lines approximate the missing surface of a model to be repaired. This field is called the missing surface field. The main idea of the concept is that calculations of a missing surface estimation method can be expressed via tension indices of this field. These tension indices created by various estimation methods can be summed to obtain the resulting ones. Thus, within the framework of the concept various methods of missing surface estimation can be used together to supplement each other and achieve better repairing results.

Keywords: cloud of points, surface reconstruction, mesh repairing, parallel architectures

1. INTRODUCTION

Creating CAD-models from cloud of points obtained by sampling the corresponding original objects is widely used in science, culture and industry. But because of various physical and technical reasons such cloud of points often contains regions with unsatisfactory allocation of the points or without them. In this case using even a powerful and robust surface reconstruction algorithm often leads to absence of the obtained model surface in the badly sampled regions. So, the problem of repairing incomplete reconstructed (damaged) CAD-models is very topical.

A majority of recently developed repairing methods can be related to two groups. Methods of the first one (let's call it the *rebuilding group*), in general, rebuild all a model to be repaired [TJ04, EBV05, ZJH07]. But it means that they ignore the most part of the previous work to create the model. Their cost of work has weak dependence on the degree of damage of the model that leads to inefficient processing little damaged models. Methods of the second group (let's call it the *template-warping group*) use warping of a suitable template from a database to repair a given damaged model region [ACP03, PMG05, SKR06]. They show impressive results, but are usable only for models corresponding to their template databases. Also, to provide proper fitting of a chosen template to the corresponding damaged model region such methods require manually setting a certain number of point matches between them.

Each existing repairing method is based on the corresponding method of missing surface estimation. In spite of the fact that even a heavily damaged CAD-model contains diverse kinds of information about its missing surface (the behavior of the reconstructed one, location of unused sampled points, a supposition of symmetry, etc) such estimation method uses only the corresponding restricted parts of it. So, using this information entirely promises significantly increasing the repairing quality with comparison of existing methods. But it is clear that developing one "universal" estimation method with this property is impossible. Thus, we have to develop a concept that provides simultaneously using several different missing surface estimation methods with possibility of these methods to supplement each other to achieve a better repairing result. The presented paper is a continuation of our previous works in the repairing theme [EM04, EAK08]. Unlike of them, in this paper the required concept is proposed. It is a general concept of an abstract field whose force lines approximate the missing surface of a model to be repaired. This field is called the *missing surface field*. The main idea of the concept is that calculations of a missing surface estimation method can be expressed via tension indices of this field. These tension indices created by various estimation methods can be summed to obtain the resulting ones. It provides the mentioned mutual supplementing of the methods. But simultaneously using several estimation methods significantly increases the cost. More generally, possibilities of the existing repairing methods are restricted by high cost of powerful missing surface estimation ones. Only way to solution this cost problem is parallelization of the repairing process using modern hardware. Its abilities allow using approaches and algorithms which even in a near past were considered extremely costly. A presented repairing method based on the missing surface field concept is an example of it. The method uses our previously developed algorithms, which are supplemented by several new quite costly ones to increase the repairing quality and robustness. But, using these algorithms significantly decreases the performance. From the architecture point of view the method implementation provides the open architecture principle that allows do develop new missing surface estimation methods by remote teams and at the same time decreases the performance as well. But good parallelization potential of the concept with the modern hardware abilities allows keeping the repairing time at an acceptable level. In general, the presented method is oriented to use on multi-processor platforms that is in agree with the modern trends in computer hardware.

The paper is organized in the following way. In the next three sections the theoretical basis of our work is described. In section 2 a formalization of assumed input is made. Then there is a description of two theoretical concepts. Section 3 explains the previously developed [EM04] *concept of bridges*. This concept considers reducing a heavily damaged model to a model that is easy to repair. In section 4 the missing surface field concept is described. In section 5 there is a description of two done algorithmic implementations of the field. Section 6 is devoted to a general overview of the developed repairing method. Some results and a discussion are in sections 7, 8.

2. FORMALIZATION OF DAMAGED CAD-MODELS

Consider a CAD-model that is an unsuccessful result of work of some surface reconstruction algorithm and has the following properties: the model contains a partially reconstructed surface ($\mathbf{A}$), with condition that each part of this surface represents the corresponding part of the original object; the remaining part of the model surface ($\bar{\mathbf{A}}$) is missing; the model can contain unused sampled points (*free points*). Let's call such model an *incomplete CAD-model* (*ICADM*). In general case, to obtain it, we need to apply a proper filtering procedure that removes all parts of $\mathbf{A}$ which don't represent the original object surface. Just an ICADM is the assumed input in our works.

In an ICADM $\mathbf{A}$ can be represented by one or several isolated coherent regions. Let's call such regions *islands*.

Any ICADM contains one or several closed boundaries which separate $\mathbf{A}$ and $\bar{\mathbf{A}}$. Each boundary has connection with one and only one region of $\bar{\mathbf{A}}$. If this region is connected only with the same boundary let's call such boundary a *hole boundary* or a *complex boundary* (*CB*) otherwise. As a consequence, the aggregate of a hole boundary and the region of $\bar{\mathbf{A}}$ that is connected with the boundary is called a *hole*.

Let's call a hole a *trivial hole* (*TH*) if its region of $\bar{\mathbf{A}}$ can be reconstructed by an existing not so complicated algorithm or a *complicated hole* (*CH*) otherwise. A boundary that is not the boundary of a trivial hole will be called a *non-trivial boundary*.

Using the terms defined above the following classification of ICADMs is made:

class	num. of islands	CB	CH	TH
ICM3	>1	y	y/n	y/n
ICM2	1	n	y	y/n
ICM1	1	n	n	y
ICMT	1	y	y/n	y/n

Note, that an ICADM can belong to class ICMT only if the corresponding original object is not a topological equivalence of a sphere and has one or several internal "tunnels" (for example, a torus-like object) which don't exist in the ICADM. In addition, each missing "tunnel" should be represented by the corresponding pair of complex boundaries and the both boundaries should belong to the same island. Such situation rarely occurs in practice, so this class is defined outside the main class sequence and is not widely considered in this paper.

3. CONCEPT OF BRIDGES

From the contents of the previous section it follows that obtaining a correct CAD-model from an ICADM of class ICM1 is not a problem. So, in general case we need a way to reduce an ICADM of class ICM3 to an ICADM of class ICM1 via intermediate ICADMs of classes ICMT (if this class is possible) and ICM2. To make it, it is enough to reconstruct $\bar{\mathbf{A}}$ only in properly chosen strip-like regions connecting the corresponding boundaries of $\mathbf{A}$ (F3.1).

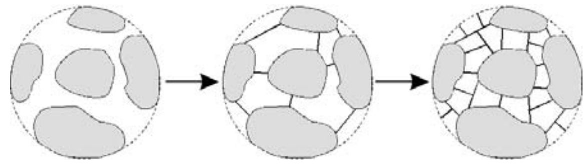

Figure F3.1

Diminishing the width of such strip region to 0 we obtain a curve connecting the two corresponding boundary points of $\mathbf{A}$; at each internal point of the curve the normal vector to $\bar{\mathbf{A}}$ is defined (F3.2). Let's call such curve a *bridge*.

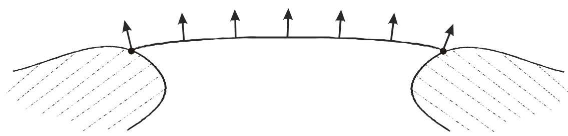

Figure F3.2

Figure F3.1 illustrates how the concept of bridges works. In the left there is a beginning ICADM of class ICM3 representing a ball-like object. Initially, using bridges we reduce it to an ICADM of class ICM2 (middle). This ICADM contains only holes, each hole boundary is formed by the corresponding bridges and fragments of island boundaries. Then using bridges again each complicated hole of the ICADM is recursively decomposed until a set of only trivial holes is obtained (right).

In this way bridges create an irregular mesh approximating $\bar{\mathbf{A}}$, inside each cell of the mesh $\bar{\mathbf{A}}$ can be reconstructed by a simple existing method (see F3.3).

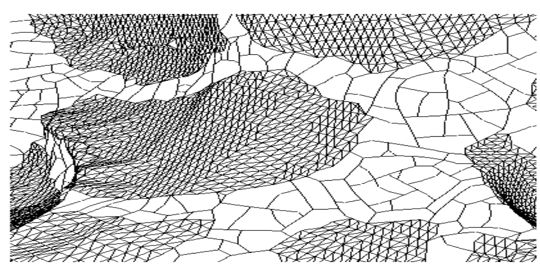

Figure F3.3

Considering that a bridge approximates the corresponding surface strip of a finite width (the width depends on a specified approximation precision) we can conclude that using the concept of bridges a major share of $\bar{\mathbf{A}}$ is reconstructed the simple method. So, using the concept significantly reduces the total repairing cost.

4. MISSING SURFACE FIELD CONCEPT

In the beginning, note that $\bar{\mathbf{A}}$ can be reconstructed only with some probability to be correct and the task of repairing a given ICADM has infinity number of acceptable solutions.

Let's suppose that in an area containing a considered ICADM there is a field of some nature. It can be considered as an instance of the missing surface field ($\bar{\mathbf{A}}F$) introduced above, if it provides obtaining the following indices at each point of the area:

- a scalar value Ψ (*potential*), such that at a specified point (X) and a point (Y) in its neighborhood $\Psi_X > \Psi_Y$ if the probability of that **Ā** passes through X is greater than the same probability for Y; non-positive values of Ψ correspond to cases when this possibility is equal to 0;
- a vector $\boldsymbol{F}$ (*force*), that indicates the likeliest direction of a bridge that passes through (incidents from) the point; the length of the vector expresses the probability of the direction to be correct in the same manner like the value of Ψ expresses the corresponding probability;
- a scalar value Ω (*attraction index*) that indices the value of the attraction component of $\boldsymbol{F}$, $\Omega \leq |\boldsymbol{F}|$, because in general case the force consists of its attractive and repulsive components;
- a vector $\boldsymbol{N}$ (*normal*) that indicates the likeliest direction of the normal to **Ā** passing through the point at the point; the length of the vector expresses the probability of its direction to be correct in the same way like the length of $\boldsymbol{F}$ expresses the corresponding probability.

Of course, if $\Psi = 0$ (for example, at a point $\in$ **A**) then $|\boldsymbol{F}| = 0$, $\Omega = 0$ and $|\boldsymbol{N}| = 0$ as well.

From the programming point of view the missing surface field can be represented by the following interface:

```
interface IMissingSurfaceField
{
 virtual void set_point(const VECTOR& point);

 virtual real get_potential() const;
 virtual void get_force(VECTOR& force) const;
 virtual real get_attraction_indexl() const;
 virtual void get_normal(VECTOR& normal) const;
};
```

Each instance of **Ā**F is implemented on the base of the corresponding missing surface estimation method. To determine the **Ā**F indices this method can require the corresponding set of extra parameters that is called the *state context* of the method.

Let's call an instance of **Ā**F a *complete* **Ā**F, if it provides obtaining all the **Ā**F indices at a point or an *incomplete* **Ā**F otherwise. An **Ā**F can be implemented as a linear composition of several (k) other **Ā**Fs with the corresponding weights (w):

$\overline{\mathrm{A}}F = \sum_{i=1}^{k} w_i \overline{\mathrm{A}}F_i$, it means that $\Psi = \sum_{i=1}^{k} w_i \Psi_i$, $\boldsymbol{F} = \sum_{i=1}^{k} w_i \boldsymbol{F}_i$, $\Omega = \sum_{i=1}^{k} w_i \Omega_i$, $\boldsymbol{N} = \sum_{i=1}^{k} w_i \boldsymbol{N}_i$ (E4.1).

Let's call such **Ā**F a *composite* **Ā**F. Components of a complete composite **Ā**F can be incomplete **Ā**Fs, with condition that obtaining each **Ā**F index is provided by at least one of its components.

Thus, the concept of **Ā**F provides joint using various missing surface estimation methods to achieve better repairing result.

In general, the relationship between the concept of **Ā**F and the concept of bridges is similar like the relationship between dynamics and kinematics in physics. Using **Ā**F we can answer to the question: "what probability of that a correct bridge passes through a specified point and what the trajectory of this bridge?" Presence of the force index allows considering **Ā**F as a force field and bridges as its force lines. But there is one fine point. From the definitions of the potential and the force vector it follows that the force vector should be collinear with the potential gradient (except several degenerated cases). But if in a used instance of **Ā**F the force vector and the potential value are determined by different estimation methods (for example, if this instance is a composite **Ā**F), then these vectors can be non-collinear in general. To keep adequate force line behavior in this situation, assume that a force line of **Ā**F is a curve such that at each point of it: all the **Ā**F indices are defined; the attraction factor isn't less than a specified threshold; the tangent vector to the curve is directed in accordance with the force vector and has a restricted deviation from it in the plane defined by the force and the normal vectors to be as close as it is possible to the potential gradient vector.

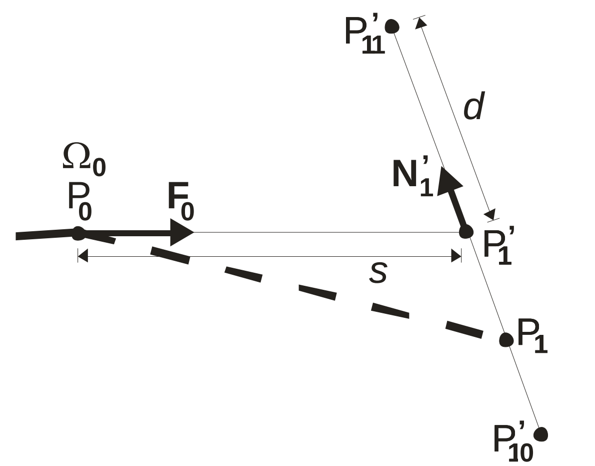

Figure F4.1

From this definition it follows that any **Ā**F force line starts and ends at the corresponding boundary points of **A**. A force line can be iteratively traced from a specified boundary point until the corresponding opposite boundary point is reached. Each tracing iteration is performed in accordance with the following algorithm (F4.1).

At a specified beginning point (P_0) the attraction factor value (Ω_0) is determined. If this value is less than a specified threshold then the tracing process is terminated as unsuccessful. Otherwise the force vector ($\boldsymbol{F}_0$) is determined at the point. Using this vector and a specified tracing step (s) the first approximation of the next force line point (P_1') is obtained. At this point the acting normal vector ($\boldsymbol{N}_1'$) is determined. Using this vector and a specified deviation limit (d) the segment of the next point searching (P_{10}', P_{11}') is determined. The point of the potential maximum on this segment is assumed as the next force line point (P_1).

In this way each force line can be traced independently on other ones. Moreover, the **Ā**F indices at a point can be determined independently on these indices at other points. It provides good parallelization abilities of implementations which use the **Ā**F concept.

In the end of this concept explanation let's define the *quality index* (q) of an **Ā**F force line:

$$q = \frac{1}{L}\int \Psi(l)dl \quad \text{(E4.2)}$$

where L is the total force line length.

5. IMPLEMENTED MISSING SURFACE FIELDS

5.1 General background

Described in this section implementations of **Ā**F are developed in a "physical" manner, so they have several common traits adduced below.

For each field the following two kinds of objects are defined: an elementary source and an object of the field action. The both kinds of objects are represented by single points supplemented by the corresponding sets of extra features (such set can be empty). An elementary source acts in the corresponding way on an object of action.

The action of an elementary source decreases with increasing the distance between it and a considered object of action. In each of the **Ā**F implementations described below this property is implemented by the corresponding distance function of the following kind:

$$\lambda(r) = 1 \text{ if } r \le r_0, \ \lambda(r) = 0 \text{ if } r \ge r_1,$$

$$\lambda(r) = \left(\frac{r_1 - r}{r_1 - r_0}\right)^p \text{ if } r_0 < r < r_1 \quad \text{(E5.1.1)}$$

where r_0, r_1, p are positive constants, $0 < r_0 < r_1$.

A has a shielding effect on **Ā**F. This effect currently implemented in the following way: an elementary source doesn't act at a specified point if the segment between this point and the point of the source crosses **A**.

5.2 Boundary interpolation missing surface field

To determine the **Ā**F indices the implementation of **Ā**F described here uses an interpolation of boundaries of **A**. Because of that it is called the b*oundary interpolation missing surface field* (*BI**Ā**F*).

Initially, let's consider the basic geometric issues. Consider a boundary of **A**, a point (O) on it, the normal vector to **A** at the point ($\boldsymbol{n}^O$), and the tangent line to the boundary at the point (F5.2.1). The tangent line splits the plane defined by O and $\boldsymbol{n}^O$ to the "occupied" and the "empty" half-planes. Define the unit vector ($\boldsymbol{\tau}^O$) on the tangent line such that the cross product $\boldsymbol{n^O} \times \boldsymbol{\tau^O}$ is in the "occupied" half-plane. Let's call such vector the *tangent vector* of a specified boundary point.

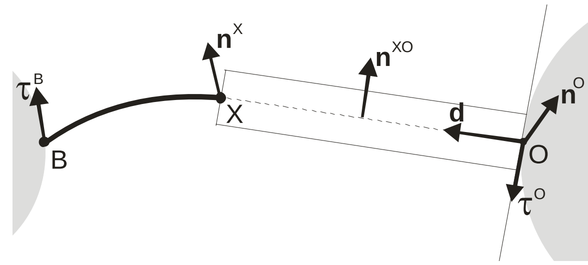

Figure F5.2.1

Consider connection of some point outside **A** (X) with **A** at O by an arbitrary narrow planar strip. It is obvious, that the plane of this strip should pass through X, O and the boundary tangent line at O.

From the vector cross-product properties it follows that the normal vector ($\boldsymbol{n}^{XO}$) of this strip is defined by the following equation:

$$\boldsymbol{n}^{XO} = \frac{\boldsymbol{s}^{XO}}{|\boldsymbol{s}^{XO}|} \quad \text{(E5.2.1)}$$

$$\text{where} \quad \boldsymbol{s}^{XO} = \boldsymbol{d}^{XO} \times \boldsymbol{\tau}^O, \ \boldsymbol{d}^{OX} = \frac{\overrightarrow{OX}}{|\overrightarrow{OX}|}.$$

Now, assuming that a normal vector at X ($\boldsymbol{n}^X$) is specified, let's define the *quality* ($\eta^{\boldsymbol{XO}}$) of the considered strip connection in the following way:

$$\eta^{\boldsymbol{XO}} = |\boldsymbol{s}^{\boldsymbol{XO}}| \left(\frac{\boldsymbol{n^O n^{XO}} + 1}{2}\right)\left(\frac{\boldsymbol{n^X n^{XO}} + 1}{2}\right) \quad \text{(E5.2.2)}$$

In this formulation the first multiplier indicates the "passability" of the strip; the second one expresses the degree of extrapolation of **A** at O by the strip; the third expresses the degree of extrapolation of an arbitrary small surface element defined by X and $\boldsymbol{n}^X$ by the strip.

Now, let's define the introduced above field. As an elementary source of the field the aggregate of a boundary point of **A** (O), the normal ($\boldsymbol{n}^O$) and the tangent vectors ($\boldsymbol{\tau}^O$) at the point ($\{O, \boldsymbol{n}^O, \boldsymbol{\tau}^O\}$) is assumed. As an object of the field action let's assume the last traced point of a force line with the origin at the corresponding boundary point (B). That is the aggregate of a space point (X), a specified normal vector at it ($\boldsymbol{n}^X$) and the tangent vector at the corresponding force line origin ($\boldsymbol{\tau^B}$): $\{X, \boldsymbol{n}^X, \boldsymbol{\tau}^B\}$. With these assumptions define the force ($\boldsymbol{F^X}$) of action of $\{O, \boldsymbol{n}^O, \boldsymbol{\tau}^O\}$ on $\{X, \boldsymbol{n}^X, \boldsymbol{\tau}^B\}$ in the following way:

$$\boldsymbol{F^X} = -c\lambda^{BI}(|XO|)\eta^{XO}\boldsymbol{d} \text{ if } \boldsymbol{\tau}^B\boldsymbol{\tau}^O < 0$$

$$\boldsymbol{F^X} = 0 \text{ if } \boldsymbol{\tau}^B\boldsymbol{\tau}^O \ge 0 \quad \text{(E5.2.3)}$$

where constant c expresses the length of the boundary segment represented by O (in other words it is a "charge value" of the elementary source); λ^{BI} is a distance function of the kind introduced by (E5.1.1).

It also can be written in the following matrix form:

$$\boldsymbol{F}^X = \mathrm{H}^X \boldsymbol{n}^X \quad \text{(E5.2.4)}$$

where

$$\mathrm{H}^X = \frac{1}{2} m \begin{bmatrix} d_x^{OX} n_x^{XO} & d_x^{OX} n_y^{XO} & d_x^{OX} n_z^{XO} & d_x^{OX} \\ d_y^{OX} n_x^{XO} & d_y^{OX} n_y^{XO} & d_y^{OX} n_z^{XO} & d_y^{OX} \\ d_z^{OX} n_x^{XO} & d_z^{OX} n_y^{XO} & d_z^{OX} n_z^{XO} & d_z^{OX} \end{bmatrix}$$

$$m = c\,|\,\mathbf{s}^{XO}\,|\,(\frac{\mathbf{n}^O\mathbf{n}^{XO}+1}{2}).$$

When the field at a point is created by a number of sources, this formulation allows obtaining the force vector for various $\boldsymbol{n}^X$ without recalculation of the matrix.

The ĀF normal vector ($\boldsymbol{N}^X$), the potential (Ψ^X) and the attraction index (Ω^X) created at X by action of $\{O, \boldsymbol{n}^O, \boldsymbol{\tau}^O\}$ on $\{X, \boldsymbol{n}^X, \boldsymbol{\tau}^B\}$ are defined in the following way:

$$\mathbf{N}^X = m\mathbf{n}^{XO} \quad \text{(E5.2.5)}$$

$$\Psi^X = \boldsymbol{N}^X \boldsymbol{n}^X \quad \text{(E5.2.6)}$$

$$\Omega^X = |\boldsymbol{F}^X| \boldsymbol{n}^X \boldsymbol{n}^{XO} \quad \text{(E5.2.7)}$$

The defined field is a complete ĀF because it provides obtaining all the ĀF indices at a point; vectors $\boldsymbol{n}^X$ and $\boldsymbol{\tau}^B$ are considered as parameters of the state context of the field.

5.3 Point radial missing surface field

This implementation of ĀF is called the *point radial missing surface field* (*PRĀF*). Its elementary source is a free point of a specified ICADM. An object of the field action is just a space point. This field is incomplete, because it provides obtaining only the potential value at a specified point. This potential, created by a free point (O) at a specified space point (X) is defined by the following equation:

$$\Psi^X = c\lambda^{PR}(|\,XO\,|) \quad \text{(E5.3.1)}$$

where $c \in (0,1]$ is the confidence value of the free point coordinates; λ^{PR} is a distance function of the kind introduced by (E5.1.1).

This ĀF can increase the adequateness of force line behavior of a composite ĀF with its participation, if a processed ICADM contains a sufficient number of free points.

6. THE IMPLEMENTED METHOD OVERVIEW

Using the theoretical basis described above a repairing method has been developed and implemented. It uses a composite ĀF that currently consists of BIĀF and PRĀF. The basic steps of the method are described in the next three subsections. These steps differ from each other in determining the characteristic value of **A** discontinuity (it used to adjust the distance function parameters of the ĀFs) and in determining the set of used elementary sources of BIĀF. The set of used elementary sources of PRĀF for these steps is the same and consists of all free points of a processed ICADM.

In the last subsection the basic properties of the method are considered.

6.1 Connection of islands

In the input of this step an ICADM of class ICM3 is assumed. Initially, for each island a set of bridges connecting it with the other ones is obtained in the following sequence:

1. the averaged inter-island span in a neighborhood of the island is taken as the characteristic value of **A** discontinuity;
2. the set of considered BIĀF sources is defined as the set of all boundary points of all the other islands;
3. at all boundary points of the island the ĀF attraction index is determined, and then the points of local maximums of the index are selected;
4. from the selected points the corresponding ĀF force lines are traced, these force lines are considered as the required bridges.

After processing all the islands, the total graph of connections is obtained. In general case this graph can contain topologically conflicting bridges. Each detected conflict situation is resolved by eliminating the necessary number of bridges with the least values of the force line quality (see E4.2).

Then, in accordance with the concept of bridges, the corresponding set of holes is extracted from the graph.

6.2 Detecting and processing lost "tunnels"

If initially, or after the previous step, the processed ICADM can be referred to class ICMT and a case of this class is admitted a priori, then this step is performed. The used algorithm allows detecting and correctly processing an internal "tunnel" if it is represented by the corresponding pair of non-trivial boundaries.

At this step the averaged distance between all non-trivial boundaries is taken as the characteristic value of **A** discontinuity. All points of these boundaries are considered as sources of BIĀF. At the same points the local ĀF attraction index is determined and then from the points of local maximums of the index the corresponding force lines are traced. When it is done, two of the boundaries are considered connected by an internal "tunnel" if two or more force lines connect them and each of these force lines has the quality higher than the quality of any other force line of these boundaries. In this case these force lines are considered as bridges. The finally obtained graph of connections is processed in the same way like in the previous step.

6.3 Decomposition of complicated holes

At this step the input consists of one coherent island with one or several complicated holes. Each of them is processed separately from other ones. Initially, the averaged size of the processed hole is taken as the characteristic value of **A** discontinuity. Then, considering all boundary points of the hole as sources of BIĀF, the boundary point with the maximal value of the ĀF attraction index is determined. From this point the corresponding force line is traced. It splits the hole to two new ones. This algorithm is recursively applied until a set of only trivial holes is obtained.

6.4 General properties

In the software realization of the method, the declared above open architecture principle, when each ĀF instance interacts with the system kernel via the interface introduced in section 4, is implemented. It gives to the system flexibility and extensibility;

also it allows developing new $\bar{A}$F implementations by remote teams of programmers.

Because the presented method works directly in regions of damage, its cost does not essentially depend on the square of **A** and as a consequence on the number of edges, triangles and points in the input. But it has a great dependence on the square and the topology of $\bar{A}$. Such dependence can't be expressed by one simple cost equation, at the same time a rough approximation can be obtained. Let's use the fact that traced $\bar{A}$F force lines finally forms a mesh of trivial holes (F3.3). Assuming for simplicity that all the force lines are traced with the same step and all the trivial holes have the same square we can conclude that the number of points, at which the $\bar{A}$F indices should be calculated, is proportional to the total square of $\bar{A}$. Assuming that the $\bar{A}$F indices calculation cost at a point is constant as well, the cost behavior can be approximated by the following expression:

$$t = kSquare(\bar{A}) \quad \text{(E6.4.1)}$$

where k is a positive constant.

It is the same dependence, like in our previous works [EM04, EAK08]. But unlike of them the actual cost value is essentially greater, because the presented method uses the quite costly algorithms described above. For example, the used force line tracing algorithm, when at each step the $\bar{A}$F potential maximum is found, is 6-8 times costlier than the previous one. Modeling the shielding property (see 5.1) and the open architecture implementation increase the cost as well.

Fortunately, the base $\bar{A}$F concept has good parallelization potential that allows compensating the mentioned above cost increasing. In the current implementation the following most costly operations are parallelized: the $\bar{A}$F attraction index calculation along boundaries; the force line tracing.

7. TESTS AND COMPARISON

Tests discussed in this section were performed using the following composite $\bar{A}$F:

$$\bar{A}F = 0.3BI\bar{A}F + 0.7PR\bar{A}F \quad \text{(E7.1)}$$

Figure F7.1 illustrates a benefit of using this $\bar{A}$F with the advanced $\bar{A}$F force line tracing. An ICADM obtained by damaging the well known "Bunny" (a) was chosen to test. The previous tracing algorithm [EAK08] provides the close-fitting reconstructed surface behavior (b). Approximately the same result is provided by the presented tracing algorithm using only BI$\bar{A}$F. But using this algorithm with the composite $\bar{A}$F allows achieving the significantly better repairing quality (c).

Information to compare the costs of the presented method, the previous one [EAK08] and our implementation of [EBV05] (*shrinking membrane* algorithm) is adduced in the table below:

method	num. of proc.	time (s)
Shrink. membrane	1	120
[EAK08]	1	90
This	1	840
This	2	470
This	8	110

All the tests were performed using the same damaged "Bunny" as the input. The presented method provides the best quality and shows a comparable time when it is performed on an 8 processor hardware platform.

Ability of the method to process heavily damaged ICADMs is shown in F7.2. Among available algorithms no one can process this sample correctly except our previous [EAK08], but its result is worse in fine details like in the test shown in F7.1.

8. CONCLUSION

The done tests demonstrate that further increasing of the robustness and the repairing quality is possible. But it requires using more and more costly missing surface estimation methods. So, parallelization of computation is only way to increase the repairing quality keeping acceptable performance indices. The introduced $\bar{A}$F concept provides good potential of development in the field of new missing surface estimation methods using and in the field of parallelization as well. As a particular, it seems perspective to supplement the done implementations of $\bar{A}$F by an implementation that uses some database of samples and a neural network. The "physical" style of the $\bar{A}$F concept corresponds to the abilities of modern GPU. Using them promises a great benefit.

The method has the proved ability to repair heavily damaged CAD-models. In general, the repairing can be performed without any manual management. At the same time, fine adjustment of some parameters (for example, the distance function power factors) allows to obtain a better result. Considering the repairing process quality as a function of these parameters, this adjustment can be made by global optimization methods using PC-clusters.

9. REFERENCES

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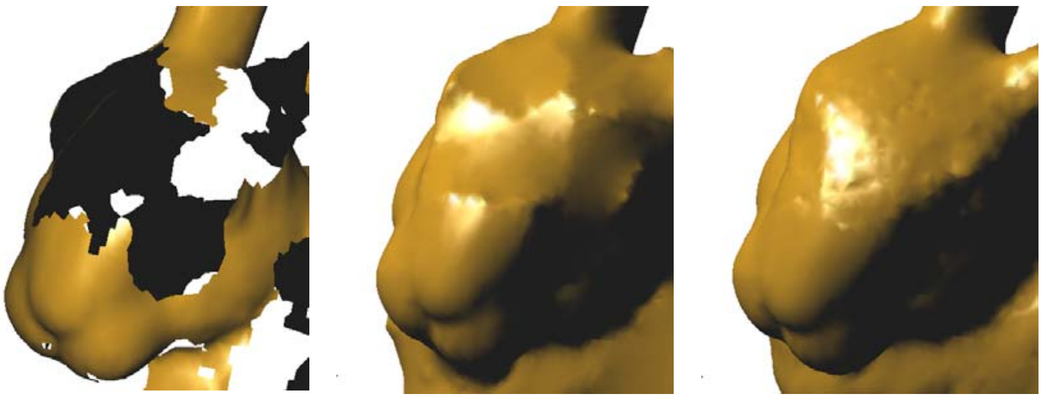

a b c

Figure F7.1: The presented method with comparison of [EAK08]

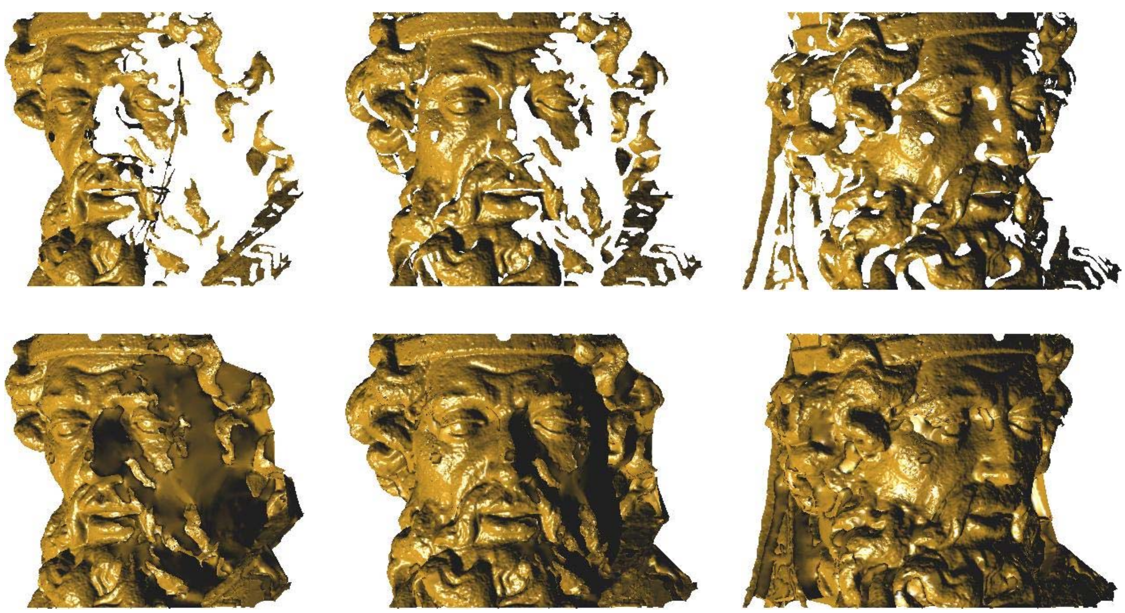

Figure F7.2: A poorly scanned sculpture fragment repairing