Title:
A Semi-Automatic Hybrid Approach for Defective Skulls Reconstruction

Authors:
Antonio Marzola, antonio.marzola@unifi.it, University of Florence, Italy
Lapo Governi, lapo.governi@unifi.it, University of Florence, Italy
Lorenzo Genitori, lorenzo.genitori@meyer.it, Children's Hospital A. Meyer of Florence, Italy
Federico Mussa, federico.mussa@meyer.it, Children's Hospital A. Meyer of Florence, Italy
Yary Volpe, yary.volpe@unifi.it, University of Florence, Italy
Rocco Furferi, rocco.furferi@unifi.it, University of Florence, Italy

Keywords:
Reverse Engineering, CAD, Skull Reconstruction, Cranioplasty.

DOI: 10.14733/cadconfP.2019.54-58

Introduction:
Cranioplasty is a neurosurgical technique to repair cranial defects, usually holes, by insertion of a cranial implant. A good restoration of the cranial integrity is critical for the brain functionality and protection, but also for the aesthetical outcome. In the last years, materials and techniques used in cranioplasty have been known an astonish evolution [1]. This is mainly due to the application of Reverse Engineering and Additive Manufacturing techniques in the medical field that, starting from Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), allows to realize customized prosthetics and implants. This evolution has brought to less implant's intra-operative adaptation need, with many advantages as regards the reduction of surgical time as well as the improvement of the clinical outcomes [7-8]. In this scenario, the proper reconstruction of the missing area in defective anatomies is proving to be one of the challenging tasks, mainly due to the wide variability of the human anatomy. Several approaches have therefore been proposed with the aim of providing a virtual coherent anatomical reconstruction of the cranial vault to be used for the pre-operative design of the corrective plate [2]. The proposed procedures could be categorized into four different strategies:

- *Mirroring-based techniques* are based on the reflection of the healthy half of the cranial vault onto the defective one.
- *Surface Interpolation-based technique*s pursue the approximation of the missing area by fitting a mathematical function which smoothly interpolates across the hole.
- *Deformed Template-based Techniques* adopt an a-priori generated 3D template of the healthy human skull properly warped on the defective skull to model the missing cranial area.
- *Slice-based techniques* use 2D diagnostic CT/MRI images to fit a mathematical closed curve to the bone contour in a slice-by-slice approach.

As reported in [2], all the presented approaches share weaknesses and limits that mainly are represented by a high user interaction request (Mirroring-based technique and Deformed Template-based Technique) or the lack of data within the hole that could affect an aesthetically acceptable reconstruction (Surface Interpolation-based Technique and Slice-based Technique).

In order to overcome these drawbacks, a new *hybrid* procedure is here proposed (see Fig. 1). The aim of such a procedure is the automatic restoration of the outer surface for a unilateral defective skull, which preserves the symmetry as much as possible when compared to the healthy half. The presented approach is *hybrid* since a surface interpolation for filling the hole is used together with a template-based reconstruction guided by the healthy counterpart.

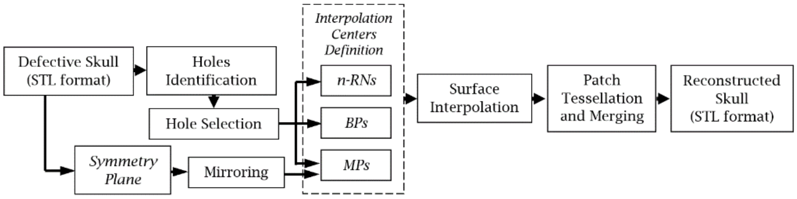


Fig. 1: The proposed procedure.

Methodology:

Starting model in STL format

The developed procedure works on surface mesh representing the defective skull in STL format obtained by a proper image segmentation from the patient's CT or MRI data. To date, much commercial software (e.g. Materialise Mimics or 3DSlicer) provide internal tools for such a segmentation as well as for exporting the obtained 3D model in STL format. Since the aim of the proposed algorithm is to restore the external shape of the cranial vault, the procedure requires only the external crust of the skull's mesh as input. For this reason, only the exterior poly-faces of the STL model are used as a starting mesh. Thanks to the regularity of the cranial vault shape, the manual operations required to the exterior poly-faces selection is straightforward.

Identification of the holes

The procedure firstly identifies the boundary edge of the skull's defects. For the edge identification, the properties of the STL is exploiting, checking each edge of the mesh, i.e. each couple of connected points, and looking for the ones which are not shared by at least two triangles. This way, in case of multiple holes the edges of all of them are retrieved. Since the proposed procedure repairs only one defect at a time, in case more holes are detected the user is required to select one point on the edge of the hole to be filled (using an appositely devised GUI). Starting from this selected point, the boundary loop of the defect under investigation is automatically defined.

Symmetry plane and Missing Points definition

To achieve a reconstruction as symmetrical as possible, the healthy half is used as a template and mirrored around a properly defined plane, henceforward named *symmetry plane*, onto the defective one. The definition of the *symmetry plane* is crucial because it must ensure a precise superimposition between the template and the defective half. This allows to obtain an acceptable outcome both in terms of the continuity at the defect's boundary and of aesthetics. For a reliable *symmetry plane* definition, in this application the method proposed by Di Angelo et al. in [5] is used, since it proved to be able to find a good approximation of skull's *symmetry plane* also in case of large defective area (i.e. in case of strong asymmetries). Once the *symmetry plane* is defined and healthy part is mirrored onto the defective one, the procedure moves away from the existing mirroring approaches; in fact, the healthy half is used only to obtain some meaningful points within the missing region instead of extrapolating the whole reconstructive patch. These points, henceforward named *Missing Points* (MPs), are selected to serve as nodes for the subsequent surface interpolation. Since the two halves are never perfectly superimposed, a simple Boolean subtract cannot be applied. Accordingly, the first step to extrapolate the MPs from the template consists of measuring the Euclidean Distance between each mirrored point and its nearest on the defective part. The nearest points are defined by means of k-Nearest Neighbors algorithm. Only the mirrored points (*query points*) whose distances to the defective points (*reference points*) are greater than an imposed threshold r_a are kept, while the others are filtered out. r_a is an input of the procedure and represents the maximum distance to search the model's points as neighbors of the mirrored ones.

Unfortunately, this step identifies the MPs of all the cranial holes. Therefore, only the MPs inside the selected boundary loop are considered. Finally, points that are at a distance less than a certain value m from the edge itself are further filtered-out to detach MPs from the boundary. m represents the minimum distance (in mm) between the boundary and its nearest ring of the MPs, as showed in Fig. 2. Too little value of m could affect the continuity between the skull and the reconstructive patch, while a too great value could be unable to lead to an acceptable outcome due to a lack of information within the hole.

Definition of the Interpolation Centers

The actual definition of the restoration patch is obtained by means of a Surface Interpolation through a properly designed points-set. Considering the missing bone as a 3D surface described by a function f: $\mathbf{R}^2 \rightarrow \mathbf{R}$ whose value $f(\boldsymbol{X_i})$ is known only on a limited number of points $\{\boldsymbol{X_i} \in \mathbf{R}^2 : i=1,2,\ldots,N\}$, it can be approximated by a properly designed function $\mathcal{S}$: $\mathbf{R}^2 \rightarrow \mathbf{R}$ which satisfies at least the *interpolation condition* $\mathcal{S}(\boldsymbol{X_i}) = f(\boldsymbol{X_i})$. $\boldsymbol{X_i}$ are called *nodes of interpolation* or *interpolation centers* i.e. the $(x, y)_i$ coordinates of each vertex i in the STL model. Several authors have proposed such an approach for the cranial vault reconstruction using different interpolation strategies [2], but the surface $\mathcal{S}$ is usually defined with the $\mathbf{x}_i$ nodes represented only by the Boundary Points (BPs), i.e. the vertices forming the edge of the defect that must be filled. This allows to achieve the geometrical continuity between the skull and the reconstructed patch thanks to the *interpolation condition* but proves to be inadequate for the correction of large defects, since the information at the boundary is insufficient to guide a coherent reconstruction within the hole. As a result, the patch tends toward a too flat shape [4]. To overcome this limitation, the proposed approach uses not only the BPs but also the above-defined MPs as nodes of interpolation. Furthermore, to ensure the continuity between the healthy bone and the corrective patch an overlapping region between the reconstructed surface $\mathcal{S}$ and the healthy skull is created by adding the *n*-Ring Neighbors (n-RNs) of the boundary loop (see Fig. 2) to the interpolation nodes i.e. the set of points within a given distance n lying in the outer side of the boundary.

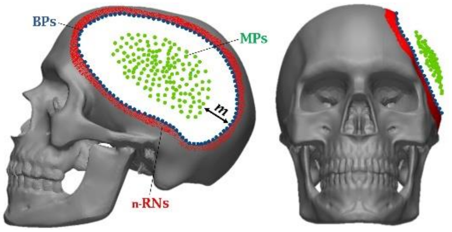


Fig. 2: The Interpolation centers set: (a) lateral view, (b) frontal view.

Surface Interpolation

Among the different surfaces $\mathcal{S}$ proposed in the related literature to solve the interpolation problem [2] (e.g. Quartic Bézier Gregory Patch, Active Control, NURBS), a Radial Basis Functions (RBF) named Thin Plate Spline (TPS) [3] have proved to be the most suitable for the proposed approach. TPS is particularly adequate because ensures a C^1 continuity, uses the *smoothest* interpolator of f [3] and guarantee the lowest computational time. Since using the TPS the *interpolation condition* is not strictly fulfilled, an iterative refinement of the surface on the *Boundary Points* to ensure an adequate continuity between the bone and the patch is required. The iterations are stopped when the following condition is reached:

$$\left| f(\boldsymbol{X_{i,BP}}) - \mathcal{S}(\boldsymbol{X_{i,BP}}) \right| < tol \qquad (1)$$

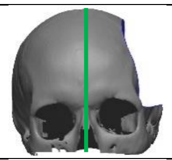
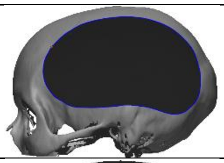
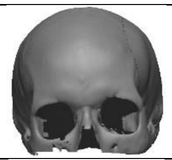
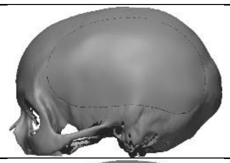
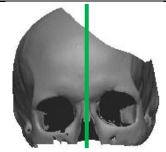
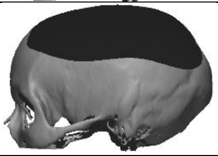
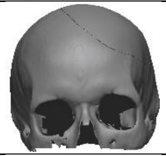
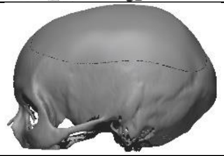
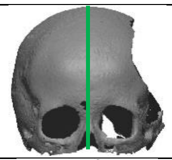
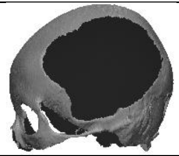
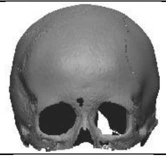
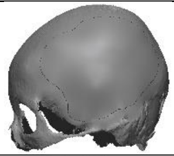
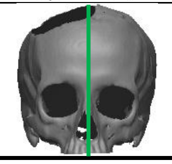
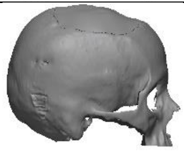
Where $f(\boldsymbol{X_{i,BP}})$ is the f value known on each BP node, $\mathcal{S}(\boldsymbol{X_{i,BP}})$ is the $\mathcal{S}$ value defined on each transformed BP node and tol the maximum tolerance imposed for the whole set of BPs. The tolerance is imposed only on the *Boundary Points* since the MPs are only useful as a reference for the coherent shape restoration within the hole, while the n-RNs are used to ensure the right curvature at the boundary. Since the application of the TPS provides a mathematical surface exceeding the defect's boundary limits, the reconstructed patch is delimited using the boundary loop. After that, the patch is tasseled, and a complete re-mesh ensures the merging between the defective STL and the reconstructed patch.

Results

Several test cases have been carried out to evaluate the accuracy of the proposed approach in the cranial shape restoration. The CT images are provided by the Children's Hospital A. Meyer of Florence and include the neurocrania from Caucasians male and female aged between 11 and 33 years, both healthy and defective. For each test case, the skull bone has been segmented and exported in STL binary format by a skilled user by means of Materialise® Mimics' tools. The external crust of each STL is then isolated using Geomagic® Design X software. The obtained STL is used as an input for the described procedure, coded in MATLAB®. In the following, the results of four test cases are reported (see Tab. 1):

- TC#1 is a complete skull with artificial holes in the left temporal bone. Two different kinds of defects are designed: the first, named *A,* is purely unilateral, while the second, named *B*, slightly crosses the *symmetry plane*.
- TC#2 and TC#3 are real defective skulls: TC#2 is a purely unilateral large defect, while in TC#3 the defect crosses the *symmetry plane*.

In all cases, the defective area is greater than 100 cm^2. Regarding the procedure's input, after a tuning of threshold parameters experimentally assessed, r_a is imposed equal to 10mm, *m* equal to 18mm and *n* equal to 50. Finally, *toll* is imposed equal to 10^{-2}, that represents a good compromise between accuracy, if compared with the CT maximum resolution (usually around 0.5 mm), and calculation time. As reported in Tab. 1, the outcomes of the presented algorithm applied to the considered test cases visually show the ability of the procedure to achieve a reliable reconstruction with regards both to the symmetry with the healthy half and the continuity between the bone and the patch. Avoiding any landmark selection or patch adaptation, the repeatability of the outcomes is also ensured. Furthermore, it results in a much simpler and less time-consuming procedure with regards to the existing approaches.

Test Case	*Defective Frontal view*	*Defective Lateral view*	*Restored Frontal view*	*Restored Lateral view*
#1_A				
#1_B				
#2				
#3				

Tab. 1: Algorithm outcomes.

For a quantitative assessment, in the related literature the main criterion for evaluating a reconstructive patch is how closely it matches the original surface. For this purpose, usually the test cases are represented by a complete skull with artificial holes [6] since the original surface of a real defective skull is rarely known. Notwithstanding, in the authors' view such a comparison does not represent a good criterion for assessing the reconstruction's outcome for the cranial vault. Since the aesthetics is considered as the most relevant aspect in the cranial vault shape restoration, the reconstruction procedure must primary ensure this outcome. For this purpose, further investigations must concern with the implementation of quantitative evaluation criteria considering that the aim of the reconstruction must be the minimization of the cranial asymmetries as well as the surface continuity between the bone and the patch, regardless how close the restored skull is to the original surface, which is unknown a priori.

Discussions and conclusions

To date, one of the toughest tasks in the cranioplasty surgery is the pre-operative virtual design of a corrective plate. To ensure an acceptable aesthetical and functional outcome, such a design must be based on a proper anatomical reconstruction usually done in virtual environments by skilled operators.

Several techniques have been developed for the cranial vault reconstruction, but all of them shared some drawbacks (e.g. too complex or time-consuming operations or incorrect resulting geometries) that limit their applicability. The difficulty is mainly due to the lack of information in the missing area and the complexity of the shape that must be restored. In order to overcome these drawbacks, a novel hole-filling procedure for the restoration of unilateral defective skulls was presented. The innovative idea was to use the mirrored healthy counterpart as a template to obtain some meaningful points in the missing region to guide the subsequent reconstruction carried out by a Surface Interpolation-based technique. The procedure works fully automatically, leaving to the user only the selection of the hole to be repaired. The test cases addressed show that the novel procedure leads to a very symmetric reconstruction with regards to the healthy counterpart, ensuring a consistent aesthetic outcome.

The procedure is suited for unilateral or quasi-unilateral (i.e. a single defect slightly passing the sagittal plane) large defects. Future work will concern the extension of the procedure applicability to all kinds of defects, including the bilateral ones. With this aim, further studies could assess a mean shape undefective skull instead of the healthy counterpart as a template, similarly to the Deformed Template-based techniques. As with the Mirroring-Based technique, basing the reconstruction upon the MPs and the subsequent surface interpolation instead of using the whole template could overcome some limitation of the Deformed Template techniques, ensuring the skull surface continuity without time-consuming user's operations.

References:

[1] Aydin, S.; Kucukyuruk, B.; Abuzayed, B.; Aydin, S.; Sanus, G. Z.: Cranioplasty: Review of materials and techniques, Journal of Neurosciences in Rural Practice, 2(2), 2011, 162-167. https://doi.org/10.4103/0976-3147.83584

[2] Buonamici, F.; Furferi, R.; Genitori, L.; Governi, L.; Marzola, A.; Mussa, F.; Volpe, Y.: Reverse engineering techniques for virtual reconstruction of defective skulls: An overview of existing approaches, Computer-Aided Design and Applications, 16(1), 2018, 103-112. https://doi.org/10.14733/cadaps.2019.103-112

[3] Carr, J. C.; Fright, R.; Beatson, R. K.: Surface interpolation with Radial Basis Function for medical imaging, IEEE Transaction on Medical Imaging, 16(1), 1997, 96-107. https://doi.org/10.1109/42.552059

[4] Chong, C. S; Lee, H. P.; Kumar, S.: Automatic hole repairing for cranioplasty using Bézier surface approximation, Journal of Craniofacial Surgery, 17(2), 2006, 344-352. https://doi.org/0.1097/100001665-200603000-00024

[5] Di Angelo, L.; Di Stefano, P.; Governi, L.; Marzola, A.; Volpe, Y.: A robust and automatic method for the best Symmetry Plane detection of the craniofacial skeletons, Symmetry, in press.

[6] Fuessinger, M. A.; Schwarz, S.; Cornelius, C.-P.; Metzger, M. C.; Ellis, E.; Probst, F.; Semper-Hogg, W.; Gass, M.; Schlager, S.: Planning of skull reconstruction based on a statistical shape model combined with geometric morphometrics, International Journal of Computer Assisted Radiology and Surgery, 13(4), 2018, 519-529. https://doi.org/10.1007/s11548-017-1674-6

[7] Girod, S..; Teschner, M.; Schrell, U.; Kevekordes, B.; Girod, B.: Computer-aided 3D simulation and prediction of craniofacial surgery: a new approach, Journal of Cranio-Facial Surgery, 29(3), 2001, 156-158. https://doi.org/10.1054/jcms.2000.0203

[8] Maravelakis, E.; David, K.; Antoniadis, A.; Manios, A.; Bilalis, N.; Papaharilaou, Y.: Reverse engineering techniques for cranioplasty: A case study, Journal of Medical Engineering and Technology, 32(2), 2008, 115-121. https://doi.org/10.1080/03091900600700749