THE F8LD MASK

Parametrized on-body design for personal protection.

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Abstract. The present research introduces a novel parametric approach for the construction of PPE, a face mask inspired from takeaway food packaging and kirigami techniques. The technique requires only foldable planar material with no gluing or binding. The design is customizable to the user's face using an augmented reality application and automatic processing in the Grasshopper environment. Using the proposed workflow, a personal mask can be constructed from a cutting and folding pattern printed on any household 2d printer. This makes it one of the most affordable and fast techniques for artisanal PPE existent now.

Keywords. Folding; ar; mask; parametric; on-body design.

1. Introduction and Problem Statement

The Covid-19 crisis has brought about many changes. People wearing masks everywhere trying to avoid contamination is probably on of the most visible ones. Through the first half of 2020 the procurement of PPE (Personal Protection Equipment) has been an important objective. Next to social distancing, PPE has been identified as the best modality to protect against SARS-COV-2 infection. The medical or artisanal mask is now a strong recommendation or a requirement in most countries touched by the pandemic. The sudden high demand has caught PPE producers off guard and has severely disrupted supply chains. The big demand has driven prices for PPE and especially masks to record highs and has depleted stocks everywhere. Until the industry managed to scale up to the demand users had to adapt. Besides conservation strategies employed for the healthcare industry (Livingston, Desai and Berkwits, 2020) a series of DIY initiatives have risen to the challenge of helping communities stay safe (Maia Chagas et al., 2020; Richterich, 2020). Different desktop fabrication techniques have been employed to replace or repair the missing equipment. The initiatives can be divided in two categories based on targeted users or used techniques. First there are the initiatives supporting the healthcare industry and that use a more standardized approach and digitally driven processes. Second, there are the artisanal and craft-based initiatives that used very basic techniques and target the general public.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 1, 503-512.

In the first category the most popular technique, due to its wide spread availability and adaptability, was additive manufacturing (AM) (Belhouideg, 2020). It found use for ventilator parts including helmets (Erickson et al., 2020), face shields (Flanagan and Ballard, 2020), masks (Swennen, Pottel and Haers, 2020; Tarfaoui et al., 2020), door handle grabbers and many others. CNC cutting of planar materials (often used in conjunction with AM) was also very popular due to very fast turnover times, simplicity and cost-effectiveness of used materials (Chaturvedi et al., 2020).

In most of the cases falling in the first category, the digital fabrication techniques were used as a substitution to industrial mass production means. They represent also a digitally assisted way of partially circumventing broken or sub-dimensioned distribution networks. In general, the digitally assisted fabrication techniques allow for the mass customization of the produced result based on design intent but more importantly on the targeted user's biometric data. Recent developments in orthosis design attest to that (Sharma et al., 2020). In the initiatives linked to the pandemics however, this aspect of customization is often very limited due to multiple reasons. The most important one is that the fabrication process is not as distributed as the users' biometric data. The mentioned fabrication processes don't have access to biometric data and more important they have no way of matching that data with the actual targeted individuals. As a result, they need to constrain themselves to small subsets of extrapolated median values and embrace a one-size-fits-all type of mentality in hope of covering as much of the user spectrum as possible.

The second category groups a set of very different approaches that make use of analogous very simple techniques for the manufacture of PPE like sewing and tailoring. Of interest here is the use of digital dissemination techniques and the distribution of the design rather than of the physical product to enhance the impact. This is possible due to the inherent simplicity of the used techniques and the wide availability of the tools and materials required for crafting the products. To give a bit of perspective, one of the most viewed tutorials for making a fabric mask has over 54 million views in 7 months on YouTube. Many studies comparing the effectiveness of artisanal and industrial PPE (Mueller et al., 2020; O'Kelly et al., 2020) avoid taking this reach aspect into consideration.

One of the advantages of the initiatives in the second category is also one of their shortcomings. The simplicity of analogous techniques ties the success of the product and its ability to do its job to the crafting abilities of the user. There is in fact very limited help from the digital technologies when it comes to making a mask. Beyond the tutorials and examples, the user is on its own when it comes to making the product and especially when adapting the design to its own measures. This often limits the reach and the effectiveness of the technique.

The problem, as it emerges from our small survey above, is that when it comes to nonindustrial PPE production and especially to masks, reach, effectiveness and cost seem to be competing metrics. With none of the initiatives being able to score in all.

2. Solution

A solution to the problem stated above is to empower the final user to produce its personal protection equipment with widely available materials and simple, prevalent household tools while also making use of the technological achievements of the 21st century for fabrication. In this context the production of a PPE mask using cutting and folding sheet material emerges as a very interesting alternative able to leverage simplicity, customization, cost and digital distribution. Even though at the time of writing this we haven't been able to find similar approaches towards making PPE masks, variants of this technique are already used on larger scales (Baerlecken et al., 2014; Vergauwen, De Temmerman and Brancart, 2014) with different degrees of computational assistance. One healthcare initiative using folding that stands out is the Apollo3 Isolation Hood (Ross et al., 2020).

In this paper we present a parametric solution that creates a disposable mask from sheet material using cutting and folding. The process works in 4 steps: 1. User face model acquisition using a smartphone's frontal camera with optional custom fitting of mask feature points. 2. Face mesh import in the CAD application Rhinoceros and automatic pattern generation. 3. Pattern printing using a 2d printer. 4. Mask creation by cutting and folding of the pattern.

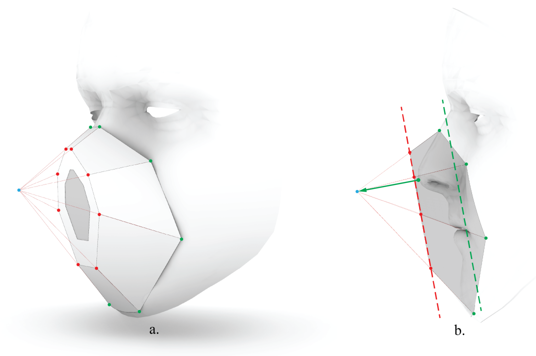

Figure 1. Geometric attributes and relation with the face for the F8LD mask.

The parametric design is based on an initial mask object (called the F8LD) created through an analogous process in the CAD software Rhinoceros. The F8LD is a disposable paper mask made from a precut sheet of material that requires only folding and no glue or fasteners for the assembly. Only a 2d printer and a paper knife or a pair of scissors are required to make the mask. The parametric version of the mask uses the features of the analogous design and extends it through mass customization. In the following paragraphs we will first present the design steps for the analogous design. After that we will elaborate on the features and enhancements brought by the parametric workflow.

3. Analogous implementation

The design is based on the polyhedral shape of an octagonal truncated pyramid. The apex of the pyramid is placed about 4 cm away from of the tip of the nose and its base points are resting on the face itself. In Figure 1 the green dots represent the feature points chosen on the scan of the face, the blue point is the apex of the pyramid. The apex is determined in several steps. First the best fit plane of the 8 feature points (the green dots excluding the nose point) picked on the face is constructed (in Figure 1.b represented as a dashed green line). Secondly the picked point representing the tip of the nose is moved in the direction of the fitted plane normal for about 4 cm to find the apex (Figure 1.b the blue dot). The red lines connecting the apex with the feature points on the face are the generatrixes of the pyramid. The top base of the truncated pyramid is constructed by intersecting a plane (in Figure 1.b represented as a dashed red line) with the generatrixes. The plane parallel with fitted plane of the face points is positioned so that the resulting truncated pyramid fully covers enclosed face features. The folding process of the mask from a planar pattern gives an overview of the design steps. The most important states of the folding process are presented in Figure 2.

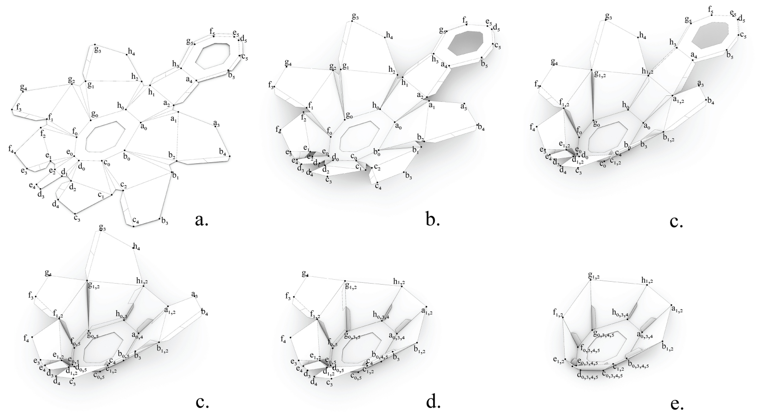

Figure 2. Screen grabs from the augmented reality application constructed to fit the mask to the face.

The fully unfolded model, presented in Figure 2.a, is an eight-arm star-shaped planar pattern containing each face of the truncated pyramid exactly twice in two concentric rings. The pattern includes several flaps and fold-in bellows. The flaps are used to keep the folded form in its shape and the bellows ensure the surface continuity in the folded state. The process reveals how folding doubles each face of the mask thus ensuring a continuous layer of material throughout the folded shape. Each vertex has a unique tag composed of a letter from a to h and a number. The letters correspond to nodes in the octagonal polygon that is the base of the pattern. The numbers denote the relationship between the points connected to the same octagon vertex but part of different folded faces.

The process starts from the flat, pre-creased pattern visible in Figure 2.a. First the bellows are folded inside to achieve the general shape of the volume. This corresponds to joining vertices with numbers *1* and *2*. This brings the faces in the first ring around the octagonal base, like *face(a0,a1,b2,b0)*, at the correct dihedral angle with the base *face(a0,b0,c0,d0,e0,f0,g0,h0)*. The process is visible in Figure 2.b and 2.c. At this step the form is not stable. The natural elasticity of the material is fighting the folds in the shape and if no force is exerted from the outside the object tends to revert to its flat version. This is resolved by folding the flattened bellows on the sides of the volume as shown in Figure 2.c. *Fold(a0,a1,a2)* and *fold(h0,h1,h2)* are bent over the *face(h0,h1,a2,a0)* and *face(h1,h3,a4,a2)* is folded over them to fix them in place as seen in Figure 2.d.

The same folding action brings down *face(a4,b5,c5,d5,e5,f5,g5,h3)* over *face(a0,b0,c0,d0,e0,f0,g0,h0)*. The folding process continues along the perimeter in two directions with *face(a1,a3,b4,b2)* and *face(g0,g1,h2,h0)* as seen in Figure 2.e. It is important to note that the mentioned faces will fold over the flaps connected to *face(a4,b5,c5,d5,e5,f5,g5,h3)* but also over the flaps connected to *face(h1,h3,a4,a2)*. The flaps connected to the latter are split and only half of them remain under the face folded next (the top half) while the other half sticks out. This ensures that consecutive folded faces like *face(g1,g3,h4,h2)* and *face(h1,h3,a4,a2)* ensure each others folded stability through a reciprocal mechanism. Figure 2.f shows the completed process with all faces folded and flaps tucked in or sticking out according to the rule.

One important, albeit optional feature of the design is the possibility to include a filtering material between the double faces of the base of the truncated pyramid. Between the folding actions shown in Figure 2.c and 2.d, a patch of filtering material can be inserted between *face(a4,b5,c5,d5,e5,f5,g5,h3)* and *face(a0,b0,c0,d0,e0,f0,g0,h0)*. The octagonal cut-out in the two faces is designed to facilitate the flow of air, through the filter. Presently one singular cut-out is designed but this can be replaced with an array of smaller holes that help to better secure the filtering material in place.

4. Evolution and parametric approach

The first iteration of the design makes for a very inexpensive and easy to distribute product either as a digital download or a precut pattern. But in this simplicity also lies one of its most important shortcomings, its lack of adaptability. Because faces come in many shapes and sizes a one-size-fits-all kind of approach does not do well, especially with semi rigid objects that need to be worn so close to the skin. The downloadable pattern can be scaled prior to printing but this in not enough to adapt it to a wide range of face shapes. In the following paragraphs we will present the additional steps undertaken to make the design parametric and customizable.

4.1. FACE MODEL ACQUISITION

The first step deals with acquiring a representation of the user face to be used for the parametric construction of the mask. In order to make the scanning process as accessible as possible we decided to use as scanning device a Time of Flight (ToF) camera. The ToF technology is present in many of today's consumer electronics and most of the new smartphones. Using ToF information the embedded software of the smartphone can construct a topologically constant but geometrically adapted model for the face of the user each time it is in view of the camera. The model is topologically constant because the constructed mesh will always have the same number of vertices and the same vertex interconnectivity, regardless of the viewed face and regardless of the face's pose. The geometry of the produced face mesh is always adapted to the user's face and represents a close 3d depiction of its features. The accuracy of the mesh compared with the real face makes possible its use as a biometric test granting access to the phone contents.

Figure 3. Screen grabs from the augmented reality application constructed to fit the mask to the face.

We propose to use this feature of modern smartphones to extract the 'scanned' face as a mesh and use it to construct our parametric mask model on it. In order to achieve this, we leverage the game engine and application development environment Unity3d with its extension for augmented reality ArFoundation. The use of Unity3d allows the construction of a custom application that can run on modern iOS or Android phones and can extract the 3d mesh representation of the user's face.

In our current workflow the application works in 3 stages. First, the application leverages, through arFoundation, Apple's arKIT and extracts a dynamic mesh very closely fitted to the user face. The mesh matches de dimensions and features of the face and can mimic all expressions (the gray overlay in in Figure 3). Second, inside the application the user can modify the eight placeholders (the red spheres in Figure 3) corresponding to the eight corners of the base of the truncated pyramid resting on the face. The transformation is done with a simplified augmented reality preview of the mask model visualized on the face of the user. In the last stage the mesh and sphere positions are exported as .obj and .txt files.

4.2. PARAMETRIC MODEL

The second step in our workflow is the automatic creation of the geometry of the mask in both its constructed (folded) state as well as in its planar pattern (unfolded) state. The scope is to construct a model that accurately and completely simulates the folded model of the mask and then use unfolding routines to make it flat. For reasons pertaining to the tools required to handle the unfolding process, the Grasshopper visual scripting environment attached to Rhinoceros was chosen as a work environment for this step.

The face mesh is imported into Rhinoceros and referenced into Grasshopper together with the eight landmarks saved with the .obj file. The landmarks are saved as a text file containing eight integer values referring to the indexes of the eight mesh vertices used as positions for the mask corners. Based on the eight positions the truncated pyramid is constructed following the same steps as the ones detailed in the solution section. The model of the truncated octagonal pyramid is constructed as a mesh that starts with 24 vertices and 16 faces. The 24 vertices correspond to the two bases of the truncated pyramid 8 on the face, 8 for the small base extending away from the face and the last 8 in the middle of the small base to define the hole for the filter. From the 16 initial faces eight are quad faces between the generatrixes of the truncated pyramid and 8 are quad faces composing the small base and fanning around the hole at its center.

In order to achieve the exact model of the mask required for unfolding, all the faces in the model need to be doubled and multiple flaps and bellows need to be added. For this scope the number of vertices is increased. In Figure 2.a the reader can follow the process and identify the individual vertices in the unfolded state as well as the multiplied vertices in the partially folded and fully folded states. The vertices defining the small base *a0* to *h0* are tripled thus producing the sets with numbers *3*,*4* and *5*. The vertices that rest on the face or set *a1* to *h1* are doubled to produce the similar set with number *2*. The multiplied vertices are necessary for the construction of the double faces in the 3d model of the folded mask. The construction of the doubled faces and thus the topology of the mesh model of the mask can be similarly followed in Figure 2. In addition to the named vertices visible in the same Figure, several other vertices are necessary for the construction of flaps. For example the flap linked to *edge(g1,g3)* is created through a 5 mm offset of the edge in the plane of the *face(g0,g1,h2,h0)* in the folded state presented in Figure 2.e. The offset line is then scaled to 80% length and connected to *edge(g1,g3)* to create the flap. The *bellow(a0,a1,a2)* is created using the geometric positions of *edge(a0,a1)* and *edge(a0,a2)* in the unfolded state shown in Figure 2.a. The fourth point of the bellow is found using the formula $\frac{a1 + a2}{2} \cdot 0.8 + a0 \cdot 0.2$. All other flaps and bellows are created in a similar manner.

4.3. UNFOLDING

The flat pattern is the result of unfolding the constructed mesh of the mask object on a plane. For unfolding we are using the Grasshopper add-on Ivy (Nejur and Steinfeld, 2016, 2017) that can unfold 2-manifold meshes of the most diverse configurations for subsequent fabrication from flat sheet materials. The add-on represents the mesh as a graph where each mesh face is a node in the graph and each 2-manifold mesh edge is an edge in the graph. The graph is a dual of the input mesh. The algorithms in Ivy make the mesh unfold by converting the constructed graph of the mesh from a graph with cycles into a tree graph. This happens by removing graph edges based on metrics chosen by the user (like dihedral angles between faces or face area). If the mesh is representable as a tree graph one can start from any mesh face and rotate neighboring faces around the common edge to have a 180-degree angle with their neighbor. If this process is followed for each subsequent neighbor, it yields an unfolded version of the mesh with no dimensional distortion.

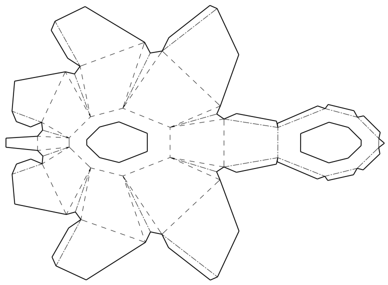


Figure 4. Fully unfolded pattern and image of a fabricated prototype being used.

For the final 2d pattern, to help the user cut and fold, we represent each edge of the unfolded mesh with a different line-type according to its role in the construction process for the mask. Cut edges are continuous, mountain edges have a dash pattern, valley edges use a dash-dot pattern while flat edges have no 2d representation. Figure 4 shows the final pattern and an image depicting the use of a prototype affixed to the face with an elastic string.

5. Discussion.

The design presented in this paper brings a new approach for the construction of nonindustrial PPE and of masks in special. It brings notions from packaging design, and tools used for geometry rationalization at the architectural scale and uses them for the creation of wearable protection. The presented design offers many advantages over the classical PPE masks in four main areas: Availability, Ecology, Cost and Adaptability.

5.1. ADVANTAGES

Availability. Since it can be delivered as a digital download all supply chains are bypassed. Getting a mask can be as fast as the time required to cut and fold the pattern from the printed sheet of paper. The materials and production tools are generally available in a typical household. **Ecology**. The typical material for the creating the mask is paper. This makes this mask biodegradable or recyclable depending on post-use decisions. Other materials can be used for the mask especially if the pattern is cut with a numerically controlled tool like a laser cutter. If more durable materials are used, like polypropylene or PET-G sheets, the mask can be used as a reusable one. **Cost**. The main cost of a mask is the cost of a printed sheet of paper. Event though our approach does not rely on industrial processes and large quantities to drive down cost it can compete in terms of cost with any

PPE mask solution currently being offered. **Adaptability**. The parametric version takes most of the advantages of the original design and adds customization. The proposed process creates a fitted mask for any user with the possibility for custom adjustment. Each mask is fitted based on individual biometric data.

5.2. LIMITATIONS.

While the parametric version improves in several areas the analogous approach, it also introduces an important shortcoming that cuts into the advantages of the original design through the required use of a commercial CAD platform to perform the creation of the unfolded pattern. For the limited scope of running the script that generates the pattern, acquiring a commercial program and the minimal skills required to use it will be too expensive and time consuming for the average intended user. Additionally, the current data exchange procedure via files can cumbersome and further cuts into the advertised advantages.

6. Conclusion and Next steps.

In this paper we have presented a parametric approach for the construction of a personal protection mask created from flat sheet material. The design is based on a scan of the user face, easily obtainable with the help of a modern smartphone fitted with a ToF camera. In the smartphone app the user can customize the position of the mask on the scan of the face and export the scan and the set positions to the Rhino/Grasshopper scripting environment. Here the complete 3d model of the mask is constructed and unfolded into a flat pattern. The pattern can be directly printed on a sheet of paper cut and folded to obtain the mask. The mask can be delivered in different ways. It can be made by the user at home from paper. It can be offered as a service that includes custom fitting by a business. It can be delivered (digitally or physically) as readymade patterns pre-tailored to a few typical face sizes. The design is open-source and the GitHub repository (Nejur, 2020) offers the work under a GPL3 licence to anyone willing to use or improve the design.

For the parametric process our next step would be to create a full integration of the mask construction and unfolding process inside the smartphone application. This would remove the requirement for a CAD framework to handle the flat-pattern creation and will improve significantly the availability and cost metrics for our proposed design. For the design, some transformations to the geometry generation process to ensure a better seal around the nose area will be undertaken. Currently due to the straight edges of the base octagon of the mask, areas of high concavity can produce gaps and partially compromise the seal of the mask to the face. We plan to address this by looking into curved folds and/or curved cuts for the base of the mask resting on the face. For the material study we plan to experiment with other flat sheet materials like PP (Polypropylene) or PET-G (Polyethylene terephthalate glycol) to test designs that can turn the mask into a reusable one. We plan to test the design on several metrics like airtightness and filtration as part future developments of the research.

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