Simplified Definition of Parameter Spaces of a Procedural Model using Sketch-based Interaction

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Abstract: This paper presents a novel technique to intuitively insert meta-parameters into a procedural model with the help of sketch-based interaction. The procedural model is represented in a GML (Generative Modeling Language) representation, which is a script language that focuses on the description of three-dimensional models. A GML model consists of a sequence of procedural modeling commands, for example extrusions. These are called with a set of local offset positions, which can be converted to global space and anchored in the surface mesh by finding reference vertices on the mesh. The system uses a deformation technique to deform the surface of the model. During the deformation, the reference vertices provide the global offset positions, whose path can be approximated by a B-spline. Exchanging the initial values of the commands by this B-spline, defines a continuous parameter space of the meta-parameter. The deformation process is supported by a mesh segmentation to create pre-defined deformation targets. Using sketch-based methods, these can be adapted to the user's needs. The results show that the system closely imitates the deformation with the help of the modeling commands. Furthermore, the system was evaluated to be intuitive and easy to use.

1 INTRODUCTION

In the context of computer graphics, the process of creating a model that represents all instances of an object is of major interest. Especially since the emergence of computer-aided design (CAD), efforts have been made to find representations of models that incorporate more information. Even with sophisticated modeling software, the development of a large model is a tedious process, thus the ability to reuse a variation of a preexisting model is of high importance.

By creating a model in a procedural way, it is possible to describe its variations. In a procedural model, a sequence of modeling commands is executed, each with a specific set of input parameters. Through the definition of their parameter spaces, possible variations of the object (an object class) can be modeled (Getto et al., 2017). However, the amount of parameters in a procedural model poses a significant obstacle during the parameter space definition.

To simplify this process, we propose a novel technique to specify the parameter spaces using sketch-based interaction and a physically plausible deformation technique. Our system is based on the models created using the sketch-based modeling tool from (Bein et al., 2009) with the extension to extract procedural models described in (Getto et al., 2017).

The system functions by allowing the user to intuitively deform the mesh that is created by the procedural model. Each parameter of the single procedures (e.g. drag or extrude) represents an offset of the control mesh that can also be interpreted as a global position in the world space. These positions can be anchored in the mesh by shooting rays to find reference vertices on the mesh surface. The global positions of the parameter offsets are now available using the barycentric coordinate on the line between the reference vertices. By evaluating the position during the deformation, B-splines for every parameter can be deduced that mathematically describe the parameter space controlled by a meta-parameter.

The goal is to provide an easy to use system, which is why the deformation is supported by an initial mesh segmentation, proposing a number of deformation handles to the user. These can further be refined with sketch-based interactions. Depending on the refinement of the segmentation, the deformation has global or local effect.

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Our contribution is composed of the technique to deduce the defined variations of the model's parameters and represent them using B-Splines. The user can specify the variations by deforming individual segments of the model. Please note that the modeling tool is not part of the contribution.

2 RELATED WORK

The definition of a procedural model is achieved by writing out a sequence of operations. (Lindenmayer, 1968) defined the L-systems (Lindenmayer, 1968), which have been repeatedly utilized to define parametric models (Herman et al., 1975; Tobler et al., 2002) or combined with shape grammars (Parish and Müller, 2001). Although powerful, the systems are highly specialized, as they need a rule set to guide the construction process and are thus not suitable for the modeling and parameterization of arbitrary shapes.

Alternatively, (Wyvill et al., 1999) combined CSG-Trees with skeletal implicit primitives as leaf nodes in their BlobTrees. By combining the field functions, they can be easily blended (Bernhardt et al., 2010) and the tree elements allow for interactive editing, swapping or removal.

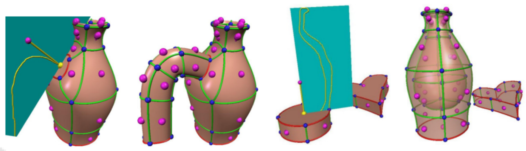
Moreover, with languages such as the stack-based Generative Modeling Language (GML) (Havemann, 2005; Havemann and Fellner, 2003), modeling operations can simply be built on top of each other. These complex operation are controlled by a small set of parameters. Using a postfix notation similar to Adobe PostScript and euler operations based on a half-edge data structure, a control mesh can be created. This will be evaluated using a modified Catmull/Clark subdivision scheme that allows for sharp edges.

Generally, sketch-based modeling systems can be classified into two categories, construction based and recognition based systems (Kazmi et al., 2014). The latter use sketches as shape descriptors and retrieve models from shape databases (e.g. (Eitz et al., 2010; Eitz et al., 2012)), which needs prior-knowledge and hence is opposed to our goal to initially define an object class. Thus, we focus on the former category.

Pioneering systems in modern sketch-based modeling inflate two-dimensional sketches of silhouettes to three-dimensional models and allow further refinement with sketch-based modeling operations (Igarashi et al., 1999; Nealen et al., 2007). However, they lack possibilities to parameterize the model and thus are not a good base for our system.

The more complex ShapeShop system (Schmidt et al., 2005) is based on BlobTrees and functions by creating and adapting a 2D template scalar field, fitting the implicit surface to the user's sketch. The hierarchical tree structure provides a number of manipulation possibilities for a meta-parameter, similar to (Schmidt and Singh, 2008) which adds layer based editing. However, the interaction with a hierarchical tree-view widget has been evaluated as unintuitive and difficult for designers (Jorge and Samavati, 2011).

(Bein et al., 2009) developed a sketch-based modeling tool based on GML. The initial sketch is converted into a control polygon using a B-spline approximation scheme and then extruded. Modeling commands such as the SketchExtrude operator (Figure 1(a)) or the RotationExtrude (Figure 1(b)) are provided. Along a sketch, the base face on the control mesh is copied and rotated (SketchExtrude) or scaled (RotationExtrude) along the path. Yet, the insertion



(a) (b)

Figure 1: The SketchExtrude operator extrudes the control mesh along a sketch path (a). In (b) a sketch is used to define the scale of the extrude along the surface normal for a RotationExtrude. Taken from (Bein et al., 2009).

of parameters is not possible, because the tool only exports the tessellation of the surface.

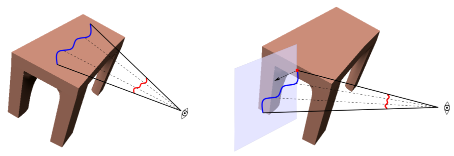
(Getto et al., 2017) extended the tool to record the construction as GML code that can be exported to a script file, which iteratively calls the modeling functions with a fixed set of parameters. Moreover, a set of rules for the insertion of meta-parameters were defined, which in turn adapt the command parameters. Although supported by a simple user interface, it is complicated and requires a high level of knowledge about the effects of each parameter. Simplifying this step is the goal of our technique, justifying the decision to use this system as a base.

Using a deformation as a target state stems from sketch-based animation. (Bessmeltsev et al., 2016) used sketched silhouettes as targets to pose an existing character model. In (Choi et al., 2016), sketched curves on joints serve as guides for the animation of characters, which inspired our use of B-splines to guide the variations.

The goal of creating a meta-representation of an object is comparable to (Fish et al., 2014; Kim et al., 2013). The difference however is that we define a shape familiy (object class) on a single instance instead of learning it from a larger set of representatives.

3 PRELIMINARIES AND USER INTERACTION

3.1 Sketch Projection



(a) (b)

Figure 2: The red line was sketched and is projected directly onto the model (a) or onto a minimum-skew viewplane (b).

The system is controlled by sketch-based user input. Usually the user has a specific kind of projection into the 3D-space in mind and the correct implementation is up to the system. Our system uses two different strategies. The user can refine an automatic segmentation with sketches (Section 3.3). In this case the sketches are perspectively projected onto the model (Figure 2(a)). However, while performing a deformation, the system needs to anticipate a projection plane. To achieve this, we use the minimal-skew viewplane projection proposed in (De Paoli and Singh, 2015). To deform the mesh along a sketch, the user naturally needs to start the sketch on the model. Thus, we can calculate the minimum-skew viewplane (Figure 2(b)) using the surface normal at the first hit point.

3.2 Mesh Refinement

After the interpretation of the script, the control mesh is subdivided to extract the limit surface. The subdivision algorithm creates a detailed tessellation in smooth areas of the object. Sharp areas are coarsely triangulated, creating areas with high anisotropy. A refinement ensures enough degrees of freedom to support small dislocations of vertices during the deformation. Because the model was previously sketched by free-handed, most triangles are smooth. We use the algorithm by (Botsch and Kobbelt, 2004), since it allows us to provide a set of triangles that need to be refined as well as a target edge length.

The median edge length $\bar{e}$ is a good target for the anisotropic triangles. To select these triangles, we calculate the interquartile range (IQR) between the lower ($\frac{n}{4}$th element) and the upper quartile ($\frac{3n}{4}$th element). Finally, the following heuristic is applied:

$$D_{out} := \{D \mid D > Q_3 + 1.5 \cdot IQR\}. \qquad (1)$$

This is a common technique to detect outliers in the explorative data analysis (Pagano, 2013).

For Section 4.1 we need to preserve correspondences between the unrefined and refined mesh, which is easily done by finding the closest vertex on the refined mesh for every unrefined vertex.

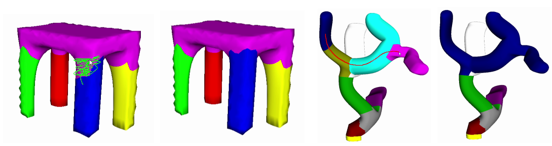
3.3 Mesh Segmentation

When using deformation algorithms, three sets of points need to be defined. Handle points are directly deformed by the user, fixed points on the other hand cannot move. The leftover points are free to move, mostly according to a specified energy function.

Having the user directly specify the fixed points in advance of each deformation would require great effort. He would have to anticipate the effects of the deformation and constrain it manually to produce the desired response. To simplify this process, we deduce the fixed points by preparing a mesh segmentation. Our system uses the algorithm by (Shapira et al., 2008), because it is invariant to pose changes and the optimal number of segments is automatically chosen. When the user starts the deformation process, all vertices outside the relevant segment are fixed. We preadjusted the algorithm to provide a liberal segmentation, hiding the parameters of the algorithm from the user, yet it might lead to more segments than the user needs. Thus, two simple sketch-based tools are introduced to refine the segmentation.

First, the user can extrude a single segment. A sketch needs to be started on the segment that is extruded and dragged over neighboring segments to overwrite the segment membership in a local region around the sketch. Figure 3(a) shows an example.

Second, if the user wants the deformation to affect more parts of the model, multiple distinct segments can be merged. This is achieved using another refinement tool, which must also be started on the segment that should be inherited by others. A sketch collects all crossed segments by projecting the points onto the model and merges them to one, as seen in Figure 3(b).

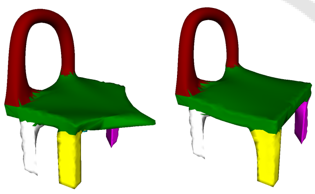


(a) (b)

Figure 3: In (a) the blue segment is extruded along a sketch and in (b) several segments are merged with the red sketch.

3.4 Mesh Deformation

After the input model has been refined and segmented, the user can start creating parameters. This is achieved by deforming the mesh. To achieve physically plausible deformation, we chose the as-rigid-as-possible deformation technique by (Sorkine and Alexa, 2007). During the deformation, the system saves one deformed intermediate mesh per sketch point. These are needed at a later stage of the parameter insertion. Our system supports three different kinds of deformations. First, by picking and dragging a point on the mesh along a sketch path, the handle points can be defined as the three vertices of the selected triangle. The fixed points are then chosen as all points outside the selected segment. However, this behavior might not be what the user intended to achieve. In the example in Figure 4(a), the intention was to change the length of the seating surface of a simple chair. Obviously, the result is far from correct, the front of the green segment would have to move uniformly together with the yellow and the pink segments. To overcome this, the system offers a second deformation handle. By choosing a segment-spanning face deformation, the handle points are spread out until a discontinuity in the face is detected. Moreover, the system temporarily merges all three segments for one deformation, creating a region of interest. The set of fixed points now only consists of all points that do not lie in the region of interest. Figure 4(b) shows the result of the same deformation with the alternative deformation handle. A third handle definition, the segment-bounded face handle, can also be utilized. It differs from the previous one, because it remains constrained by the original segment.



(a) (b)

Figure 4: Deformation of the chair's seating surface with the standard deformation handle (a) and the segment-spanning handle (b).

4 PARAMETER INSERTION TECHNIQUE

After the deformation process, the system needs to determine the mathematical definitions of the intended meta-parameter. By varying this meta-parameter in the interval $[0,1]$, the procedural model interpolates the deformation process as closely as possible.

4.1 Command Analysis

A two-stage process decides, which commands of the script are relevant. By analyzing the deformed mesh, a set of displaced points $\mathcal{V}$ is formed. The derived set is then checked against each step of the procedural model's construction process. To improve the runtime, not all vertices of the deformed segment are included in the set $\mathcal{V}$:

1. The deformation process works on the refined mesh with a much larger number of vertices than the original mesh. Only working on the vertices on the refined mesh, that correspond to a vertex on the unrefined mesh, reduces the size. The correspondence is described in Section 3.2.
2. Furthermore, all vertices outside the region of interest (ROI) can be excluded from the set. This set of segments contains the vertices that are not fixed. Thus, they are the only ones that could possibly be moved by the deformation.
3. For vertices in a small local region, the displacement distances usually are almost identical. Thus, all vertices with similar movement can be omitted. Also, experiments revealed that it is sufficient to only use the top 20% of the remaining vertices, as these represent the characteristic movements of the deformation.

After having specified the set of characteristic deformation vertices $\mathcal{V}$, they can be used to identify the commands that must be parameterized. Conceptually, this is done by executing the GML script one command at a time (Algorithm 1). In each step, the surface of the constructed model is checked against $\mathcal{V}$. If any point is directly on the surface of the model, the last executed command must be parameterized. For this purpose, the algorithm iterates over each control face. If it contains smooth edges, it has to be subdivided before the testing. Afterwards all detected vertices are removed from the set, because they would be false-positive results in every subsequent step. The algorithm terminates, when the set $\mathcal{V}$ is empty or all commands have been executed.

An additional function (Line 8) checks, whether the currently executed command is a construction command. In total, the sketch-based modeling tool supports 17 modeling commands, however not all of them are needed to adapt the model to the deformation, as some commands e.g. only change the sharpness of a control point. We identified the following six modeling commands as relevant: NewObject, SketchExtrude, RotationExtrude, DragFace, DragEdge, DragVertex.

For example, each picture in Figure 5 results by

Algorithm 1: Identify Commands.

```
function IdentifyCommands(𝒱)
    𝓘𝓓 := ∅
    for i = 0 to 𝒞.size() do
        if 𝒱 = ∅ then
            exit
        end if
        Execute(𝒞[i])
        if IsConstructionCommand(𝒞[i])
          ∧ PointOnModel(𝒱) then
            𝓘𝓓.insert(i)
        end if
    end for
    return 𝓘𝓓
end function

function PointOnModel(𝒱)
    pointOnModel ← False
    for all f ∈ ℱ do
        if f is smooth then
            patch ← Subdivide(f)
        else
            patch ← f
        end if
        for all v ∈ 𝒱 do
            if Distance(v, patch) < ε then
                pointOnModel ← True
                𝒱.remove(v)
            end if
        end for
    end for
    return pointOnModel
end function
```

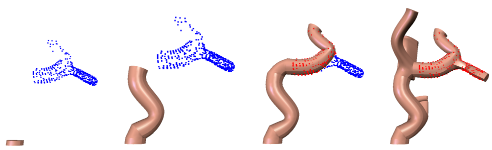


Figure 5: The iterative construction process of the procedural model after command 1 (a), 2 (b), 3 (c) and 7 (d).

executing subsequent construction commands. Additionally, the characteristic deformation vertices are shown in blue. After performing the first two commands 5(a) and (b), none of the points are on the surface of the created model. However, after the execution of 5(c), a subset of $\mathcal{V}$ (red) coincides with the models limit surface. After several more commands, the command executed in 5(d) detects all remaining points in $\mathcal{V}$, resulting in $\mathcal{V} = \emptyset$ and terminating the algorithm. The result of Algorithm 1 for our example is $\mathcal{ID} = \{3,7\}$.

4.2 Tracking the Offsets

During the deformation, the system stored intermediate steps for every sketch point. This is important, because a user sketch is not necessarily a straight line. One thing that all the relevant modeling commands have in common is that each builds on some form of point position. These can be either in form of cylindrical coordinates with respect to the command's base face (SketchExtrude and drag commands), global point positions (NewObject) or more abstract extrude data (RotationExtrude). All of them can (if needed) be converted to global points that lie either inside the undeformed mesh or on its surface. Inversely, the changed global offset positions can be monitored. If the position is directly on the surface of the mesh, this is especially simple. Otherwise, reference vertices have to be chosen, so that the global offset position lies on the line defined by these vertices. Then the position is described by the barycentric coordinate on that line. Depending on the command type, the reference vertices have to be chosen differently.

4.3 SketchExtrude

A SketchExtrude command has several parameters. Figure 6(a) is a close-up view of the base face of a sketch extrusion. What is already known to us are its midpoint, its face normal n and an arbitrary orthogonal vector o in the faces plane that defines $\phi = 0$ of the cylindrical coordinate system. Furthermore, we know the offsets of each new face along the extrude path as cylindrical coordinates with respect to the previous face. By converting them into cartesian world coordinates and iteratively adding them to the base faces midpoint, we can calculate the global positions g_i inside the deformable mesh: $g_i = \sum_{j=0}^{i} l_j$.

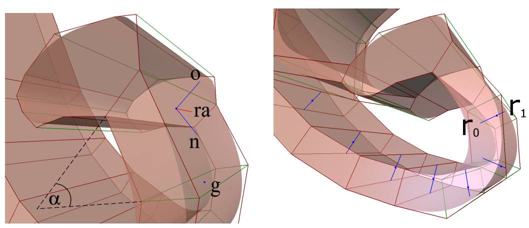


Figure 6: In (a) the structure of the first extrude of a SketchExtrude is shown. (b) visualizes the reference lines.

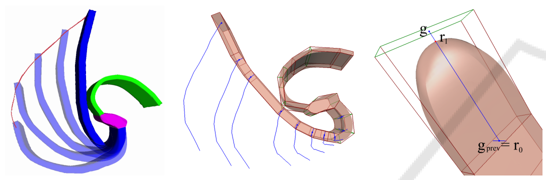
To create a link between the surface mesh and the point inside the model, we rotate the orthogonal vector o by the corresponding angle α of each extrude step around the rotation axis ra. By shooting a ray from g in the vectors direction and its opposite direction, two reference vertices on the model's surface r_0

and r_1 are retrieved (Figure 6(b)). These vertices can be tracked during the deformation of the mesh. By calculating the barycentric coordinates λ of g on the line $\overline{r_0 r_1}$ before the deformation, the position of g can be derived in any arbitrary deformation step:

$$\lambda_g = \frac{|r_1 - g|}{|r_1 - r_0|} \quad , r_1, r_2 \in \mathcal{D}_0 \tag{2}$$

$$\Rightarrow g_{def} = r_1 - \lambda_g \cdot (r_1 - r_0) \quad , r_1, r_2 \in \mathcal{D}_i. \tag{3}$$

Figure 7(a) shows a deformation along the red sketch. Using the precomputed barycentric coordinate λ, the position of g in the deformed meshes is evaluated. This yields a discrete set of deformed global positions for each original g, which is approximated by B-splines using the method presented in (Bein et al., 2009) and is shown in Figure 7(b). Via interpolation of the B-splines with a parameter $t \in [0,1]$, an arbitrary deformation state can be recreated.



(a) (b) (c)

Figure 7: During the deformation intermediate steps are saved (a). These are used to evaluate the global offset positions per step, which form B-splines (b). Figure (c) shows the anchoring scheme at an end piece of a SketchExtrude.

If the SketchExtrude contains discontinuous parts, it can happen that the reference line is of bad quality. In this case, the reference line is much longer than the other ones and the point g tends to be far from the middle of the line. To resolve such an issue, the reference line is rotated until it is of good quality. The rotation axis is retrieved by rotating the base face's normal n similarly to the orthogonal vector.

So far, all global positions were located inside the model. Yet, if the command was used to model an end piece of the object, the last g is not necessarily inside the model. Depending on the sharpness of the last control face, it either lies on the surface or outside the model. The global offset position g of the end piece in Figure 7(c) lies outside the model, thus it cannot be anchored in the mesh using the same concept. Alternatively, a ray is shot from the previous point inside the model g_{prev} in the direction of g. An intersection with the models surface is detected, providing r_1. Although g_{prev} is not a vertex of D_0, we have already anchored it in the mesh, thus it can be utilized as r_0. With both reference vertices, the position of g outside the mesh can be evaluated. This time however, $\lambda > 1$ is used to extrapolate outside the bounds of the line connecting r_0 and r_1.

Now that the B-splines describing the offsets of the SketchExtrude commands can be created, they are inserted into the script. At the same time, a meta-parameter $p \in [0,1]$ is added, which constitutes the parameter p of the B-splines $B(p)$. A value of $p = 0$ leaves the model as it was before, while $p = 1$ corresponds to the fully deformed mesh. When rebuilding the model, the evaluation of the B-Splines yields the positions of the offset points g. Moreover, two steps are needed in preparation of the command:

1. In case more than one parameter applies to the same command, their influence is summed up and the final cylindrical coordinates are calculated.

2. The local angles need to be reevaluated, since they were only valid for the original undeformed model. They are calculated using the evaluated positions from the B-Splines. For each extruded face, the rotation angle α_i with respect to the commands base face is the angle between the base faces normal vector n_0 and the vector from the previous point g_{i-1} to the next g_{i+1}. The rotation axis ra is used as a constant rotation direction.

$$\phi(u,v) := \cos^{-1} \frac{u \cdot v}{|u| \cdot |v|} \tag{4}$$

$$l_i = \begin{cases} g_{i+1} - g_{i-1} & , i \in \{1, \dots, n-1\} \\ g_{i+1} - g_i & , i = n \end{cases} \tag{5}$$

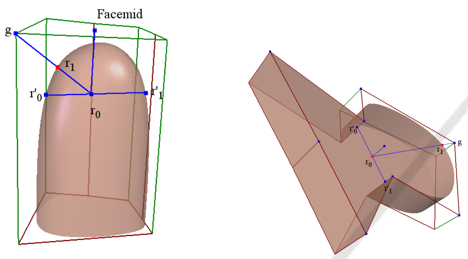
$$\alpha_i = \begin{cases} 2\pi - \phi(n_0, l_i) & , ra \cdot (n_0 \times l_i) < 0 \\ \phi(n_0, l_i) & , \text{else.} \end{cases} \tag{6}$$

4.4 DragFace, DragVertex, DragEdge & NewObject

The DragFace command is similar to a SketchExtrude that only performs a single extrude and thus functions analogous to its end case (Figure 7(c)). However, we have no previous position g_{prev} to use as a reference vertex. Because of this, we shoot a ray from g in the opposite direction of the face normal into the model. The intersection point is r_1 and by following the ray a little further into the model we choose an arbitrary point inside the mesh as r_0. Since the second point is again not fixed in the mesh, we use the same technique as in the general case of the SketchExtrude to track its position, hence we have two more reference vertices r'_0 and r'_1 to anchor r_0.

GML uses a half-edge data structure, thus an edge is always associated with one vertex. Due to this, the DragVertex and DragEdge commands use the same parameters. Instead of tracking a position in the middle of a dragged control face, we are interested in a vertex of the face. However, the approach is similar: From g, we shoot a ray back inside the mesh to find r_0 which is anchored using a reference line in orthogonal direction (r'_0 and r'_1). From r_0 another ray is shot towards the vertex of the control face and the intersection with the mesh gives us r_1 (see Figure 8(a)).

The NewObject command has no offsets in cylindrical coordinates, but only control points of the initial sketch. These are combined to a face and extruded by 0.5 units in the opposite direction of the face normal. Thus, we shoot a ray from the face midpoint in the opposite direction of the face normal and stop after 0.25 units to find a point in the middle of the mesh r_0. From there, we shoot rays towards the control points and use the intersections as r_1 (see Figure 8(b)).



(a) (b)

Figure 8: The anchoring schemes for a DragVertex / DragEdge (a) and a NewObject command (b).

4.5 RotationExtrude

The RotationExtrude command is similar to the SketchExtrude, as both can be used to construct new geometry. While the latter employs the user sketch to define the path of the extrude, the former has a fixed direction. It always extrudes by l_i along the normal of the base face. As a consequence, the command-parameters are suitable to elongate and scale the structure. The sketch is used to define the scale s_i of each new face, as compared to the base face. However, a user-guided deformation does not necessarily follow these constraints, because a deformation often bends a structure. Thus, the RotationExtrude command needs to be adapted in order for it to be able to follow a deformation similarly to a SketchExtrude. We calculate the positions g of the new extruded faces on the face normal and apply the same technique as in Section 4.3.

A SketchExtrude needs a rotation normal ra to calculate the local angles, which is lacking in this command. During the evaluation, ra is deduced, by taking the cross product of the vector from the base face g_0 to g_1 in the original state and the same vector in an arbitrarily deformed step:

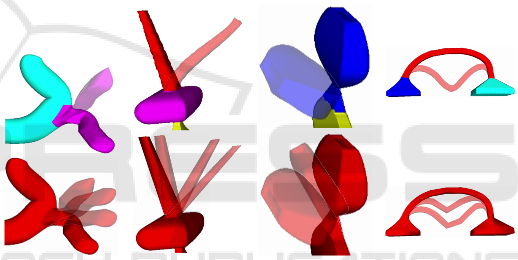
$$ra = (g_{1,orig} - g_{0,orig}) \times (g_{1,def} - g_{0,def}). \quad (7)$$

During the evaluation of the procedural model, the calculated offsets are simply used to move the control vertices.

5 RESULTS

We used several minimal procedural models to test the parameterization of each modeling command separately. In Figures 9(a) - (c) a selection of them are presented. Their successful processing demonstrates that the single parts of the system work individually.

Furthermore, it is important that the parameterization of a command does not vary subsequent parts. In the example in Figure 9(d) only the red segment was deformed by the user and it can be seen that the resulting variations comply to this constraint.



(a) (b) (c) (d)

Figure 9: Minimal examples of SketchExtrude (a), DragFace (b) and RotationExtrude (c). Figure (d) demonstrates that subsequent commands are not affected. The user deformation is on the top and some samples of the model on the bottom.

Usually, not all variations of an object can be described with a single deformation, but it is thus necessary to introduce more than one meta-parameter into the procedural model. Revisiting the previous example, we performed another sidewards deformation on the handle in Figure 9(d). Now both parameters are regarded in a single command, leading to a two dimensional parameter space. A sampling of this space is shown in Figure 10.

In Figure 4(b) we already introduced the example of a chair, whose seating surface should vary in length. With the help of the alternative deformation handle, the system was able to create a meta-parameter to control this length. Figure 11 presents some of the variations.

Finally, we tested the system with more complex models that better resemble real world applications. The procedural model of the plane used in Figure

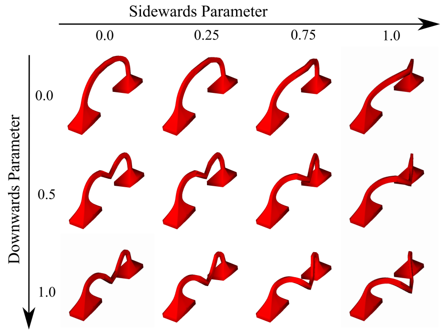
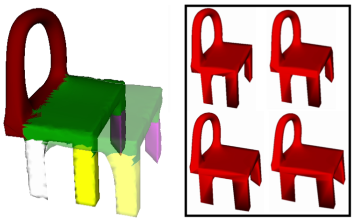


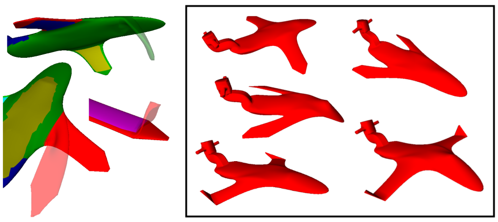
Figure 10: After a downwards and a sidewards deformation, two parameters are inserted. A sampling of the parameter space is shown.



(a) (b)

Figure 11: Using the segment-spanning face handle, the chair was deformed (a). Figure (b) shows results of the GML model with different parameter values.

12 is composed of 76 modeling commands and the user introduced five meta-parameters that vary the angle of the cockpit, the wings and their tips. With the help of only five intuitive deformations, the user quickly defined the desired parameter spaces and created a procedural model that describes a range of different planes. Some of the deformations are visualized in Figure 12(a). By varying the values of the meta-parameters, the plane changes its structure in the bounds of the defined object class. Figure 12(b) shows a number of samples, generated by randomly varying the meta-parameters between 0 and 1.



(a) (b)

Figure 12: Several deformations have been performed on the mesh of a plane (a). Figure (b) gives results of the model with multiple parameters using different values.

The system was presented to four test users with a brief introduction of the functionality. They were asked, if the interaction with the system was perceived as intuitive. Both the sketch-based refinement of the segmentation and the deformation matter in this question. The users generally agreed, that the sketch-based interaction was easy to use and had a flat learning curve. Furthermore, it was asked if the resulting parameterized model represents what the user had in mind prior to the interaction. After trying out the system for five minutes, the users understood the effects of the different deformation handles and were able to create predictable results.

However, the dependability on the deformation algorithm is a major limitation. Our technique can only create meta-parameters that follow the deformation steps. To overcome this limitation more user interaction would be needed. For example an inflation tool could be used to vary the scales of a RotationExtrude. Furthermore, the degrees of freedom of the GML model are limited. A SketchExtrude command only performs a fixed number of extrude operations, thus it cannot interpolate every arbitrary deformation. Inserting another extrude in the middle of the script to increase the degree of freedom is not possible, because the sketch-based modeling tool our technique is based on uses an id-based system to reference each face. Another extrude inserts more faces, making the face references of the subsequent commands invalid.

6 CONCLUSION AND FUTURE WORK

We presented a technique to intuitively insert meta-parameters into a procedural GML model with the help of sketch-based interaction. The system derives global offset positions from the GML commands. These are then anchored in the evaluated surface mesh by finding reference vertices and saving their spatial relationship to the global positions. During a deformation, the points are tracked and the path of the offsets is approximated with B-spline curves. These are then inserted into the procedural algorithm and evaluated according to the value of a corresponding meta-parameter. To ensure ease of use, an automatic segmentation provides deformation targets that can be refined using sketch-based interaction. Also, the behavior of the deformation algorithm can be easily adapted. The results validated that the proposed technique is a powerful tool, opening the possibilities of procedural modeling to a broader audience.

In the future we plan to extent the variations that can be defined with a meta-parameter. Perceptual knowledge can help to identify changes that seem natural to the user and can be used to improve the deformation process. Also, the integration of the modeling tool and our system will help to overcome the latter limitation.

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