

Short Papers

Structured Mechanical Collage

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Abstract—We present a method to build 3D structured mechanical collages consisting of numerous elements from the database given artist-designed proxy models. The construction is guided by some graphic design principles, namely unity, variety and contrast. Our results are visually more pleasing than previous works as confirmed by a user study.

Index Terms—3D modeling, collage, shape synthesis, part assembly

1 INTRODUCTION

DIGITAL 3D mechanical collages, such as humanoid robots, are highly demanded in applications such as computer games and sci-fi movies. Such models typically consist of hundreds or thousands of elements or parts. Therefore, building such mechanical models with standard modeling tools, e.g., Autodesk Maya, requires professional skills and is still a tedious task even for skilled users.

Like the production of other art forms, the design of digital mechanical models generally undergoes a coarse-to-fine process. It often starts with a coarse proxy 3D model, e.g., Fig. 2a, which is used as a starting point for a final model with fine details. Constructing such details is often achieved by manually picking and placing suitable elements, and thus a very time-consuming, tedious process even for moderately detailed models. Hence it poses an interesting research problem of how to speed up the design process by automating part assembly with respect to the proxy model from the artist, such that the artist can focus only on the creative side of the process.

Existing 3D collage techniques [1], [2] may not be suitable for addressing the design problem of digital mechanical collages. When elements of large size, i.e., comparable to the size of proxy components, are used to form a collage of mechanical elements, the resulting models lack sufficient detail as shown in Fig. 2b. In contrast, when many elements of smaller size are used, the assembled models look chaotic as shown in Fig. 2d and fail to inherit the component structure from the proxy model as shown in Fig. 2a.

To address these issues, we propose a *structured* 3D collage technique for building visually well-structured digital mechanical collages by automatically assembling elements from a repository of mechanical elements with respect to artist-designed proxy models (Fig. 1). We focus on synthesizing highly detailed mechanical collages, of which proper arrangement of elements is more important (Figs. 2 and 3). Our solution is inspired by some of the graphic design principles, namely: unity, variety and contrast (Section 3.1). We show how these principles can be computationally modeled and used together to produce controllable and structured 3D collages. Visual cohesiveness and interest are achieved by employing these principles at different stages of the assembling process.

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We have applied our technique to various artist-designed proxy models of different complexity, shape, structure and style. Results show that our technique is able to automatically produce visually pleasing collages of mechanical elements, leading to highly detailed and structured mechanical collages without user intervention. A user study shows that our technique creates perceptually more visible structures and aesthetically more pleasing collages than the 3D collage technique [1]. In this paper, we mainly use robots to illustrate our ideas due to their popularity in games and movies, but we also show other types of mechanical collages produced by our techniques.

2 RELATED WORK

Existing 2D or 3D collage techniques attempt to solve a common core problem: finding an assembly of elements that maximizes fitting while minimizing the interaction between elements. For example, Gal et al. [1] present an iterative collage updating approach. For each step, it chooses the best surface-fitting element which satisfies the overlap and visibility constraints. The techniques by Theobalt et al. [2] and Huang et al. [3] first divide a target shape or image into segments and then fit to each of them a single shape primitive from a repository of elements. All these techniques do not have any control of perceptual structure in the generated collages and thus simply prefer elements of large size to avoid chaotic appearances. In contrast, our approach concentrates on the arrangement of elements within a proxy model such that the resulting collages are visually structured even when small elements are used.

Our approach is closely related to example-based model synthesis [4], [5], [6], [7] or discrete element texturing [8], [9]. These methods might be used together with a coarse-scale target domain to control the overall resulting shape. However, their goal is to synthesize large models or discrete elements in a large domain according to a small input exemplar. Hence, the synthesized results exhibit strong self-similarity or repetition, which rarely appears in digital robots. Another similar problem is discrete element packing, which aims to pack a set of elements into a target domain or shape. The elements used there are often of small size (compared to the target domain) but self-similar (e.g., rocks [10] or text characters [11], [12]).

Our problem is a special problem of assembly-based 3D modeling, for which a variety of user interfaces have been proposed (e.g., [13], [14]). It is only until recently that several automatic part assembly approaches have been introduced for either open-ended 3D modeling [15], [16] or structure recovery from scan acquisition [17]. These approaches heavily rely on part-level semantic information or positional information with respect to entire models in the repository, while there is no such information associated with the elements or parts in our repository.

The perception of visual clutter or complexity has been an important research topic in the fields of cognition and computer vision (e.g., [18], [19]). Recently, Ramanarayanan et al. [20] take the first step to understand the perception of complex aggregates of realistic objects for graphics. Nan et al. [21] present a computational framework to model conjoining Gestalt rules. Although there exist various methods for measuring visual complexity or clutter, how to effectively use such metrics to guide a model synthesis process is still unclear.

3 METHODOLOGY

In this section, we first present several graphic design principles that we have found useful for our problem and then show how to computationally model them towards structured 3D collages.

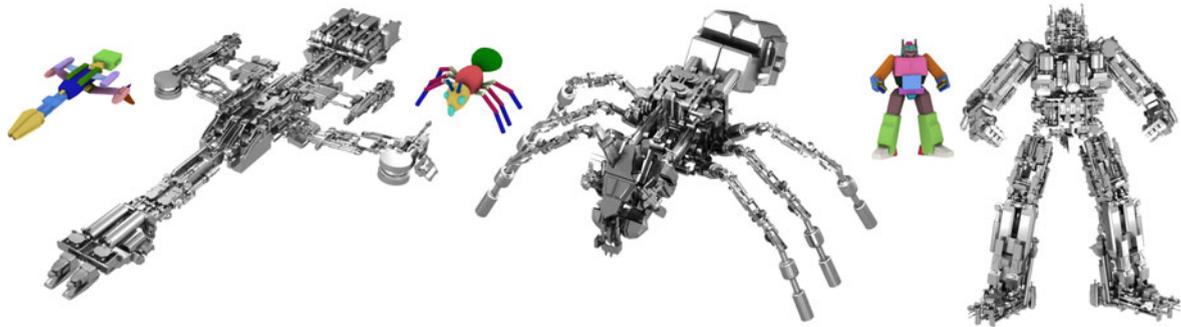


Fig. 1. Given coarse proxy models designed by an artist, our technique automatically produces highly detailed and structured 3D collages of mechanical elements, which faithfully reflect the artist's design intention and are visually pleasing.

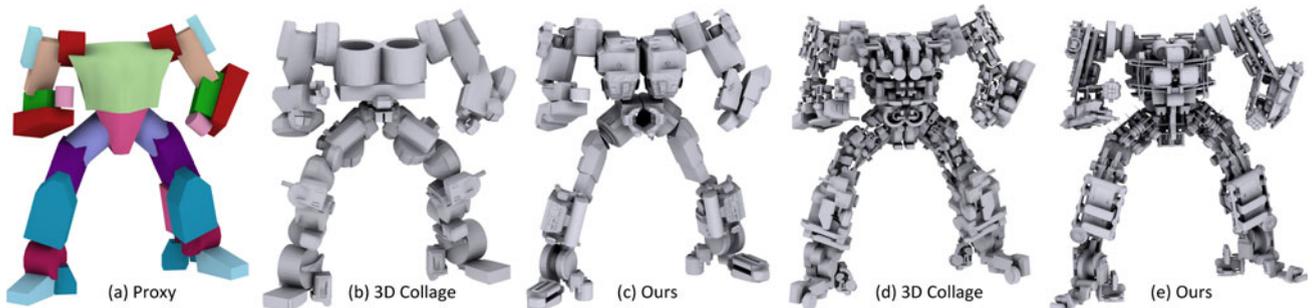


Fig. 2. Using large elements, our result in (c) is comparable to that by 3D collage [1] in (b). However, for producing detailed models, our result in (e) exhibits more visual interest and perceptual structure than that by 3D collage in (d).

3.1 Design Principles

Our problem bears strong resemblance to one of the problems in graphic design: the arrangement of visual elements in some type of media (e.g., webpages). While graphic design is a creative process, there exist a few basic principles that appear in every well-designed piece of artwork. Here, we give a brief overview of several such guidelines that are closely relevant to our problem. Note that such principles are interdependent, though they are discussed separately.

Unity generally refers to the overall cohesiveness of element arrangement. Well-designed unity makes separate elements appear to be unified, connected, and interrelated. The design principle of unity is closely related to the Gestalt theory of visual perception [22], [23]. As such, ways to enhance unity include *proximity, similarity, symmetry, repetition, and continuation*.

Variety attempts to accomplish the opposite of unity [24]. However, if all elements have variety and are different from one another, e.g., in form, size, color, and/or shape, the resulting collages would look chaotic and disordered. On the other hand, too much unity looks boring. Hence, variety must be used together with unity, as seen in most successful designs, though either of them can be emphasized, up to the designer.

Contrast is one of the most effective ways to add visual interest to a design and to create an organization hierarchy among different elements [25]. It is often used to attract a viewer's attention to specific parts of a design. Contrast is created when elements are

significantly different in terms of e.g., shape, size, direction and color. For contrast to be effective, it must be strong and selective. For example, attempting to apply contrast to all elements often leads to no contrast at all.

Our work focuses on the application of the above basic principles to structured 3D collage synthesis, though we are aware of other principles such as proportion, balance and rhythm. We refer the interested reader to [22], [24], [25]. To reflect the artist's design intention, i.e., the component structure of the proxy model, we propose to apply unity with variety to the arrangement of elements *within* individual proxy components (Section 3.2) and apply contrast *between* proxy components (Section 3.3). This allows artists to focus on the design of the proxy models and provides them an easy tool to add visual interest to the collages.

3.2 Unity with Variety

As previously described, unity and variety essentially compete with each other. We take a two-step approach to strike a balance between them. First, we create a well-connected collage but without any unity control (Section 3.2.1), thus automatically leading to great variety. Second, we iteratively perform a series of unification operations until the desired degree of unity is reached (Section 3.2.2). Compared to an alternative approach that starts with unity followed by variety, our approach allows a more precise control on the style of unity exhibited in the final model.

Element repository. We downloaded some CAD models and robot models from the Internet and disassembled them into basic parts as the elements in our repository. (See their thumbnail images in the supplementary, which can be found on the Computer Society Digital Library at <http://doi.ieeecomputersociety.org/10.1109/TVCG.2014.2303087>.) In total, there are 209 elements in our data set. The reference coordinate system and size of each element are manually specified. The size of the proxy model relative to the average size of repository elements influences the overall collage resolution and is controlled by the user to suit his/her design intent.



Fig. 3. Filling the proxy (left) using 3D collage (middle) and our method (right). Our method emphasizes on internal structure while 3D collage emphasizes on surface fitting.



Fig. 4. Examples of connectors and good connections.

Connectors. Mechanical connections are important in order for the collage to appear well connected. In our implementation, we have mainly considered two types of connectors: male connectors and female connectors, as shown in Fig. 4. A female connector is generally a receptacle that receives and holds the male connector. When a male connector of an element is connected with a female connector of another element, it is said to be a *good connection*. During the pre-processing stage, all such connectors are manually specified for each element in the repository. Here it may be interesting to note that from our observation, the relative sizes of the male and female connectors do not really affect the visual appearance of the connection. This greatly increases the chances of forming good connections.

3.2.1 Element Assembling with Variety

The input to our algorithm is an artist-designed proxy model, which roughly depicts a desired global shape with separate components representing different body parts of a collage (Fig. 2a). Below we first describe how to select and assemble suitable mechanical elements from the preprocessed repository to approximate a given proxy component.

A highly detailed mechanical collage created by an artist often contains details spread in space such that internal structures can be partially seen from the outside. Hence, unlike the approach of Gal et al. [1], which explicitly searches for best-fit elements with respect to the proxy surface and simply places them along the surface, we adopt a hybrid approach and use the proxy surface only as a soft constraint.

Let E be a repository of mechanical elements and E' a set of elements already placed in the proxy component. Starting from E' , we use an iterative growing algorithm to fill the space of the proxy component until the desired space density is reached (see the assembling animation in the accompanying video). As a new element $e \in E$ is added to E' , it may intersect with E' at multiple places forming several connections $\{p_k\}$, where $1 \leq k \leq N$. While some connections may form good connections, others may not. We observed that the visibility of good connections will influence mechanical plausibility of a collage, as shown in Fig. 5. This motivated us to bring good connections near to the proxy surface and bury poor connections inside.

To achieve this we introduce the following score function, which is illustrated in Fig. 6:

$$f(e) = \frac{F(e)}{N} \sum_{k=1}^N (D_c(p_k)G(p_k) + D_s(p_k)(1 - G(p_k))), \quad (1)$$



Fig. 6. Illustration of Eq (1). A new element (yellow) is placed into a proxy (black lines), intersecting with existing elements at P_i . Left: we prefer to place the element forming two good connections with existing elements near the boundary of the proxy. Right: we prefer to place the element forming two bad connections near the proxy center.

where $D_c(p_k)$ and $D_s(p_k)$ are the distances from p_k to the medial axis and to the surface of the proxy, respectively. $G(p_k)$ indicates if p_k is a good connection, i.e., 1, or not, i.e., 0. Here, $F(e) = I(e) \cdot P(e) \cdot (1 - R(e)) \cdot T(e)$, with $I(e)$ denoting the ratio of e 's volume not covered by E' to minimize intersection with the existing elements, $P(e)$ the ratio of e 's volume inside the proxy to minimize protrusion, and $R(e)$ the density of the local unoccupied space surrounding e to encourage a more uniform distribution of elements in the space. Both $I(e)$ and $P(e)$ have minimum cutoff thresholds, below which their values become 0. These are hard constraints. $T(e)$ is a multiplier that favors elements being oriented along the same direction as the proxy component, defined as $\alpha|d_e \cdot d_p|$ ($\alpha = 10$ in our implementation). d_e and d_p are directions of e and the proxy component, respectively, determined by their longest bounding box edges.

Iterative growing. Initially $E' = \emptyset$. The first element in E that has $F(e) > 0$ is selected and placed near the proxy surface where the element locally best matches the surface (similar to [1]). For each growing iteration, we first *randomize* E while taking into account the design parameters (Section 3.3). We then select the elements one by one from E until we identify the *first* element e that satisfies the following constraints: at least one element in E' forms good connections with e ; if e is added as part of the collage, e should not seriously intersect with the existing elements (i.e., $I(e)$ is below a certain threshold), and should not protrude too far from the proxy component to respect its shape (i.e., $P(e)$ is below a certain threshold). To determine the position and orientation of e , we check all possible transformations that translate and rotate e keeping at least one good connection with an element in E' . To limit the search space, only 48 axis-aligned orientations are used: 6 (positive/negative axis directions) \times 4 (rotations along each axis direction) \times 2 (mirror reflection w.r.t. a plane perpendicular to an axis direction). e is finally placed into E' by the transformation that leads to the maximum value of $f(e)$. Several iterations are shown in Fig. 7.

Since E is always randomized before being sequentially examined, it is guaranteed that the above approach can lead to great variety in shape and size. Our approach deliberately allows multiple instances of a single element to appear in the collage, since repeated elements often occur in artist-created models. This also makes it unnecessary to collect a large repository of mechanical elements. On the other hand, we penalize an element if it has been selected too many times in the same collage, which otherwise would cause the collage to look repetitive and boring.

For simplicity, to create a full collage, we independently apply the above procedure to individual proxy components (Fig. 8). We



Fig. 7. Iteration 2, 3, 4, 12, 27 in the iterative growing process. Previous and new elements are colored in grey and orange.

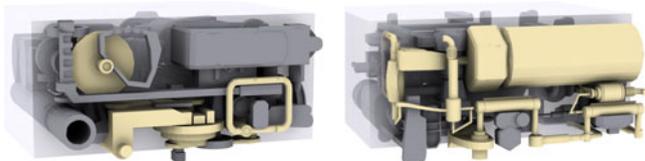


Fig. 5. Without (left)/with (right) hiding poor connections. Elements forming good connections are colored in yellow.

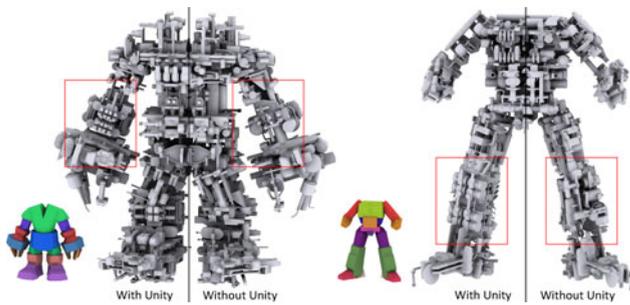


Fig. 8. Our results with unity control (left half of the collages) appear more structured than those without (right half of the collages), particularly in the highlighted regions.

make component-wise collages symmetrical for proxy components that have a symmetry relationship as indicated by the artist (e.g., left and right half of the body). Only reflective symmetry is used in our implementation. This simple solution may cause poor connections between elements from adjacent proxy components. A better solution might be to grow the collage component by component, which will be experimented in the future.

3.2.2 Iterative Unification

Now we introduce our iterative unification algorithm, which iteratively modifies the assembled collage *within each proxy component* to reach the desired degree of unity. As mentioned earlier, there are multiple ways to enhance unity, mainly through some combination of the Gestalt principles. As a proof of concept, our work mainly uses reflective symmetry (Fig. 8), which is widely adopted by graphic designers for a similar purpose. Note that the overall approach described below is general and applicable to other principles or their combinations.

Chaos metric. We first introduce a metric to measure the amount of chaos between a pair of collage elements. Our metric is based on four observations. First, the degree of chaos can be decreased by similarity and alignment. Second, as the distance between the two elements increases, the degree of chaos decreases due to the decrease in the level of interaction between them. Third, chaos is less noticeable when the elements are partially occluded by other elements. Fourth, when the size of one element is significantly different from that of the other element, the larger element will be perceptually dominant, thus reducing the amount of chaos. Specifically, the degree of chaos between a pair of collage elements, denoted as e_i and e_j , is defined as follows:

$$o(e_i, e_j) = O_s \cdot O_d \cdot O_b \cdot O_r. \quad (2)$$

Here O_s , O_d , O_b and O_r are functions of e_i and e_j , defined based on the above four observations. Specifically, $O_s(e_i, e_j) = 2 - I(e_i, e_j) - S(e_i, e_j)$, where $I(e_i, e_j) = 1$ if e_i and e_j have the same identity; $I(e_i, e_j) = 0$, otherwise. Similarly we have $S(e_i, e_j) = 1$ if e_i and e_j are symmetric; $S(e_i, e_j) = 0$, otherwise. $O_d(e_i, e_j) = 1 / (\|p_i - p_j\| + \epsilon)$, where p_i is the centroid position of e_i and ϵ is a tiny value to avoid division by zero. $O_b(e_i, e_j) = (1 - \frac{2D_s((p_i + p_j)/2)}{l_{proxy}})^{\alpha}$, with l_{proxy} denoting the diagonal length of the bounding box of the relevant

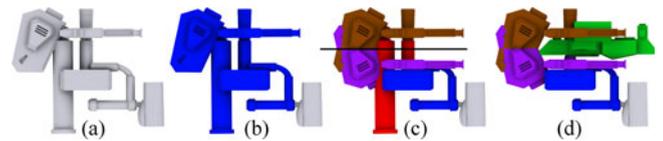


Fig. 10. (a) Original. (b) A set of elements (blue) are selected for symmetrization. (c) Symmetry plane (black line) is determined. Some elements are selected (brown) and reflected (purple). Overlapping elements are deleted (red). (e) New elements (green) are added to maintain the desired density. See the demo in the accompanying video.

proxy component and $\alpha = 2$ in our implementation. Finally, $O_r(e_i, e_j) = \min(V_i, V_j) / \max(V_i, V_j)$, where V_i is the volume of e_i . Fig. 9 shows some examples of the effect of these factors.

The amount of chaos for a proxy component is defined as the sum of the amounts of chaos for all pairs of elements in the proxy component. Note that more elements of similar sizes but different shapes generally lead to higher chaos. On the other hand, the amount of chaos is minimized when the collage consists of multiple instances of the same element, uniformly distributed on a regular grid. Our iterative unification algorithm to be introduced next essentially forms a hierarchical organization of the elements in the collage (similar to the symmetry hierarchy in [26]). We measure the amount of chaos for such a hierarchically organized collage using a bottom-up approach, where the chaos metric in Eq. (2) is similarly defined between any two groups of elements.

Iterative symmetrization. Our iterative symmetrization step is to reduce the amount of chaos for a collage to a desired value. As shown in Fig. 10, each iteration consists of three basic steps: first pick a set of elements or groups of elements to be symmetrized, then symmetrize them, and finally delete or insert new elements to satisfy the desired density. We introduce each step in more detail next.

To effectively reduce the amount of chaos, in each iteration we would like to pick a set of elements (or groups of elements in a hierarchically organized collage) that are rather chaotic (Fig. 10b). To this end, we start with a collage element i^* with $i^* = \operatorname{argmax}_i \sum_{j \neq i} o(e_i, e_j)$. Starting with $M = \{e_{i^*}\}$, we insert elements to M one by one in a BFS-like manner. (Note that the element assembling process discussed in Section 3.2.1 essentially produces a tree structure that captures the connection information among the synthesized elements.) It stops growing if the symmetrization of M would lead to a desired amount of chaos reduction (e.g., 30 percent of the total amount of chaos of the initial collage).

Our symmetrization step identifies a symmetry plane that divides M into two parts. The part M^+ , whose symmetric copy does not protrude the convex hull of M too far, will be selected for symmetrization (Fig. 10c). For the remaining part M^- , the elements that overlap with the symmetric copy of M^+ will be deleted. However, when evaluating symmetry planes, for efficiency we assume that M^- will be completely deleted so as to quickly approximate the final collage M' . We find the best symmetry plane according to two guidelines. First, the symmetrization should respect the overall shape of M , which we approximate by comparing the convex hulls of M and M' . Second, the number of elements should be kept approximately the same in M and M' . We exhaustively search for such a plane by scanning through a number of equally spaced axis-aligned planes intersecting with the convex hull of M .

Finally, we check the density of the resulting collage (Fig. 10d). If it is below the desired value, we call the assembling algorithm (Section 3.2.1) until reaching the desired density. If the density is too high, we remove elements one by one, from the proxy center to the surface but without seriously breaking element connectivity. Fig. 11 shows the effect of different amounts of chaos reduction.

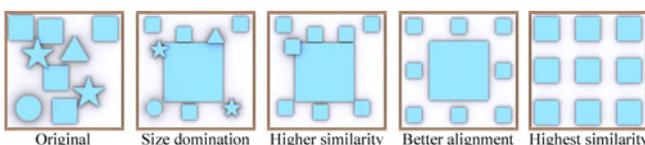


Fig. 9. Elements arranged in decreasing chaos. The reason for chaos reduction is stated below each arrangement.

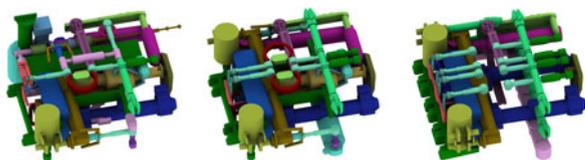


Fig. 11. Varying the amount of chaos reduction from the original. From left to right: 0, 60 and 95 percent reduction.

3.3 Contrast

While the above approach is able to produce well-structured collages for individual proxy components, assembling all component-wise collages in the same way often leads to a full collage that looks boring, mainly due to the lack of contrast (e.g., Fig. 12b). In addition, such resulting collages often fail to reveal the artist's intention, i.e., the structure of the original proxy model. To address these issues, we propose to enhance the contrast between neighboring components of the proxy model. This may be used as a tool to direct the viewer's attention to specific parts of the collage, which has not been experimented yet.

For simplicity, we assume that the component neighborhood information comes with the proxy model, e.g., manually assigned by the artist. To ensure that all neighboring components have different styles and thus have the contrast effect, we use a greedy graph coloring approach such that no two adjacent vertices (i.e., proxy components) share the same color (i.e., style). We have found that four colors are sufficient for all the proxy models used in our experiments. We mainly use the size information to implement the contrast effect and define four colors as follows: $s = (u_v, u_{ar})$, where u_v and u_{ar} are binary digits. All the elements in the repository E are classified into two groups, labeled as $u_v = 0$ or 1, based on their volumes. Similarly, they are also labeled as $u_{ar} = 0$ or 1 according to their aspect ratios (defined as the length of the longest edge of its bounding box divided by the average length of the other two edges.). Each element then has its associated color, denoted as $s^e = (u_v^e, u_{ar}^e)$.

We notice that for a proxy component with a specific color, simply using the elements with the same color to fill it often leads to a full collage with too strong contrast (Fig. 13(left)). To address the problem, we use the following interpolation equation to relax the contrast: $\bar{s} = (1 - \beta)s + \beta(I - s)$, where $I = (1, 1)$, $\beta \in [0, 0.5]$ is a weight to control the degree of relaxation, s and $\bar{s} = (\bar{u}_v, \bar{u}_{ar})$ are the styles (or colors) associated with each proxy component before and after relaxation, respectively. Fig. 13 shows the effect of varying β . $\beta = 0$ reduces to the original color assignment, leading to the maximum contrast, while $\beta = 0.5$ causes very low contrast, as all proxy components are controlled by the same averaged style. We find that $\beta \in [0.05, 0.15]$ strikes a good balance in our experiments.

After relaxation, the desired style \bar{s} for each proxy component no longer consists of binary digits. To determine the appropriate elements needed to achieve the desired style, we sort the elements in E such that those which can bring the style of the collage in the proxy component closer to \bar{s} are more likely to be selected first. The sorting is repeated at the beginning of *each* growing iteration in



Fig. 12. Contrast control, which mimics the contrast effect, is often adopted by artists (e.g., lots of small elements used in the lower body part of (c)).



Fig. 13. Left: Maximum contrast ($\beta = 0$). Middle: Moderate contrast ($\beta = 0.1$). Right: Low contrast ($\beta = 0.5$).

element assembling (Section 3.2.1). Let E' be the set of elements already in the partially completed collage. The style of E' , denoted as $s' = (u'_v, u'_{ar})$, is defined as the average style over all the elements in E' : $s' = \sum_{e_i \in E'} V_i s^{e_i} / V$, where V_i and V are the volumes of element e_i and the proxy component, respectively. For each $e_i \in E$, we check how it helps achieve \bar{s} if e_i is added to E' . Let $s'' = (u''_v, u''_{ar})$ be the style of $E' \cup \{e_i\}$. The contribution of e_i towards the realization of \bar{s} is then defined as $\Delta_s(e_i) = w \cdot \Delta_v(e_i) + (1 - w) \cdot \Delta_{ar}(e_i)$, where $\Delta_v(e_i) = |u'_v - \bar{u}_v| - |u''_v - \bar{u}_v|$ and $\Delta_{ar}(e_i) = |u'_{ar} - \bar{u}_{ar}| - |u''_{ar} - \bar{u}_{ar}|$ are e_i 's contributions towards the realization of \bar{u}_v and \bar{u}_{ar} , respectively. $w = 0.8$ in our implementation. We assign each element e_i a score, which will be used for sorting: $score(e_i) = r \cdot (\Delta(e_i) - \min_j \Delta(e_j) + \xi)$, where r is a random number between 0 and 1 to introduce certain degree of randomness to the contrast effect, and $\xi = 0.001$ in our implementation. Finally we sort the elements in E in descending order based on $score(e_i)$ and pass the sorted elements to element assembling. Fig. 12 shows an example with and without using contrast.

4 IMPLEMENTATION DETAILS

Volumetric representation. The element assembling step in Section 3.2.1 involves repeated intersection tests, which are costly to compute for polygonal meshes. We thus use a volumetric representation to speed up the process. The individual terms in Equation (1) are evaluated using 3D convolution, taking advantage of existing highly optimized GPU libraries.

Functional elements. A mechanical collage may contain elements to meet its functional requirements, such as joints, wheels and guns. An automatic approach to place these elements requires accurate shape understanding. Instead, we allow the user to manually place these functional elements in the proxy, which are then fixed and connected to elements that are automatically inserted during the collaging process. Fig. 14 shows an example created with manually specified joints.

5 RESULTS AND DISCUSSION

We have tested our method on various artist-designed proxy models of different complexities, shapes and styles. As shown in Fig. 1 and Fig. 18, the collages automatically generated by our algorithm are highly detailed but still visually pleasing and well structured. All of them are generated under both unity and contrast control.

Timings. The unoptimized implementation of our algorithm (in MATLAB with JACKET GPU library) took about 60 minutes to



Fig. 14. A hand proxy (left), with manually specified joints in blue (right). Other elements are automatically filled.

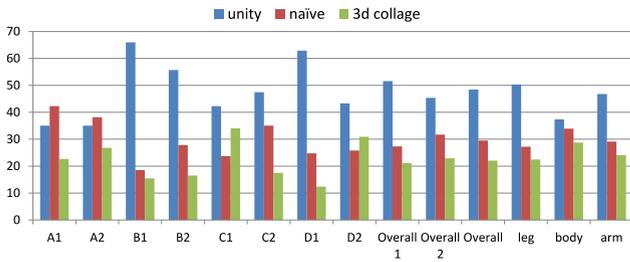


Fig. 15. Normalized votes for each set of collages. "Overall 1" and "Overall 2" show the total votes for cases using small-sized elements (A1,B1,C1,D1) and medium-sized elements (A2,B2,C2,D2), respectively. "Overall" shows the overall results.

generate the collage shown in Fig. 2e, which contains a total of 720 elements (360 elements being mirrored). The experiments were conducted on a PC with an Intel i7 3.1 GHz CPU, Nvidia GTX580 GPU and 18 GB RAM. The assembling step takes about 65 percent of the total time while the unification takes the rest. Note that the unification stage also calls the assembling algorithm in case of excessive deletion of elements. If such time is counted towards the assembling time, then assembling takes 85 percent of the total time.

Parameters. A pilot study shows that different proxy components might need different degrees of unity. Generally speaking, the closer a proxy component is to the global symmetry plane indicated by the artist, the lower degree of unity it requires. This is reasonable, since global symmetrization enhances the unity of relevant proxy components, while proxy components that are away from the global symmetry planes need more local symmetrization operations in order to achieve similar degree of unity.

User study. Compared to contrast, the effect of unity might be visually subtle. We have thus conducted a user study to evaluate the effectiveness of unity alone, i.e., without applying contrast. The state-of-the-art 3D collage algorithm [1] is also included in the user study. We have included three methods for comparison in the user study: the state-of-the-art 3D collage method [1], the naive method (i.e., our method without unity nor contrast) and our method (with unity alone). For fair comparison, we restrict the orientation of each element in the 3D collage to be one of the 48 orientations.

We used four proxy models of various shapes and generated two types of collages: highly detailed (i.e., using elements of small size) and moderately detailed (i.e., using elements of medium size). We do not include low detailed collages of large elements in the user study as they already have high degree of unity even without any unity control. We had a total of 97 participants in the user study. Each user was shown eight sets of collages. For each set, we showed the participant three collages (randomly ordered) produced by the three methods. We then

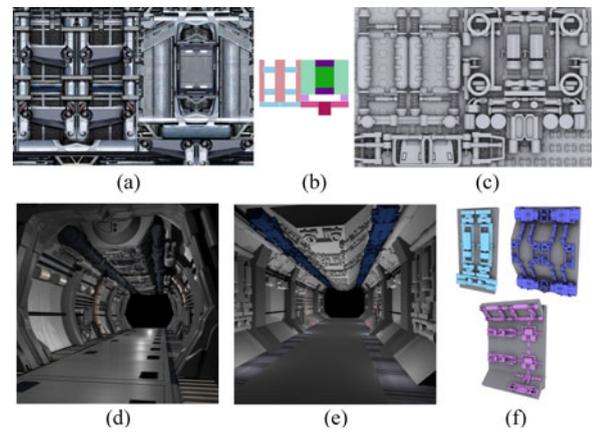


Fig. 17. (a) Reference sci-fi texture. (b) Proxy model. (c) Generated texture. (d) Reference scene. (e) Synthesized scene with geometric texture blocks shown in (f).

asked him/her to indicate the preferred component-wise collage for every part (i.e., proxy component) of the proxy model as well as the whole collage. Fig. 16 shows two sets of collages that we used in the user study. See the supplementary, available online, for the other examples.

Fig. 15 plots the normalized votes for the eight sets of collages. When the whole collages are considered, pairwise comparisons show that overall our method significantly outperforms the 3D collage and the naive methods ($p < 0.01$) for both highly detailed and moderately detailed collages. The advantage of unity is more obvious for the highly detailed collages, e.g., B1 (containing more than 1,600 elements, Fig. 16(right)). Unity is less useful when the original collage is not very chaotic, e.g., A1 and A2 (for which spatial density is set to the lowest (0.35)). In particular, for A1 (Fig. 16 (left)), participants favor the arms of the collage by the naive method over our result mainly due to the excessive empty space in the latter. When individual parts are considered, the effect of unity is more obvious for the legs and arms ($p < 0.01$). Note that there is no statistically significant difference for body parts, since we deliberately used a low degree of unity in them.

Application to texture design. In addition to mechanical collages, our method can also be used to generate 2D or geometric sci-fi textures, which are widely used in futuristic scenes and objects. Such textures are composed of mechanical elements and require certain degree of unity to be visually pleasing. We may generate such textures using a thin proxy, as shown in Fig. 17.

Limitations and future works. We manually annotated each element in the repository, which took about 2 minutes for each. A semi-automatic approach for example based on slippage analysis

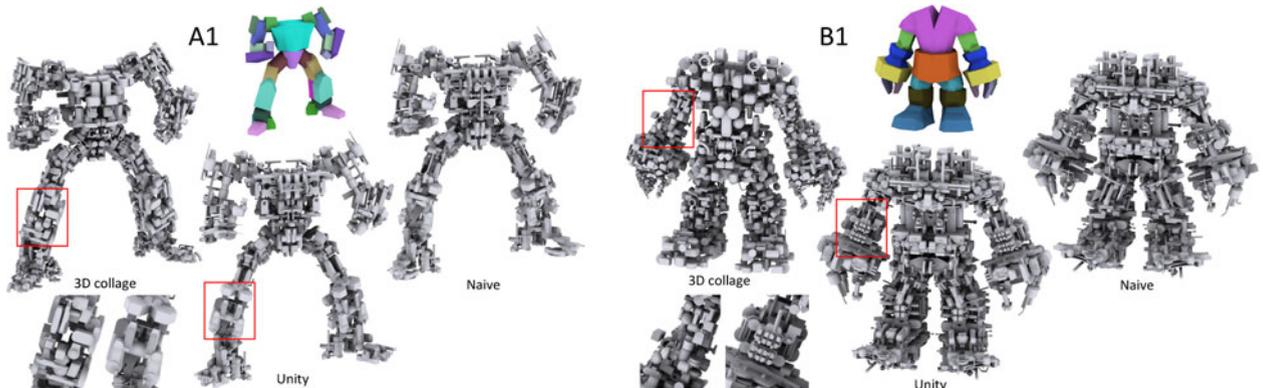


Fig. 16. Two representative sets of collages used in our user study. See the supplementary, available online, for the other sets of collages.



Fig. 18. Additional results showing an elephant, an engine, a rifle, and a space station.

(to detect connectors) might be developed to speed up the process of preparing the element repository. Due to the exhaustive search involved in element assembly, our algorithm is still too slow for interactive control. Our current unification step mainly relies on symmetrization. Thus, the results shown in this paper exhibit similar style of structure. This may be enriched by exploiting more graphic design principles to guide element assembling. Our contrast control is currently applied between neighboring components. This does not guarantee that a viewer's attention can be directed to a specific part of a collage, which is interesting to explore in the future. Lastly, it is found that artists often embed functional or semantic parts into their design while our current method is purely geometric.

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