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Reflection Symmetry in Textured Sewing Patterns

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(a) input (b) [Wolff et al. 2019] (c) ours: global reflection symmetry

Figure 1: *Our method improves visual appearance for garments with automatically aligned textures along seams by incorporating the reflection symmetry of the human body. Our input is a sewing pattern and the desired fabric print - a 2D wallpaper pattern (a). Recent work by Wolff and Sorkine-Hornung [WS19] describes a method to align repetitive textile prints along seams and optimizes this fit by slightly deforming the sewing pattern. The resulting texture alignment, sewing pattern and 3D garment shape are not globally symmetric (b). We expand this existing method and incorporate the global reflection symmetry of the human body, as defined by the user. The resulting sewing pattern and 3D garment shape are symmetric and show improved visual appearance (c). Even though we increase the number of constraints, the quality of the texture alignment along individual seams is not visibly affected. The mismatch at each seam edge is visualized on a color scale from green (0 cm) to red (2 cm).*

Abstract

Recent work in the area of digital fabrication of clothes focuses on repetitive print patterns, specifically the 17 wallpaper groups, and their alignment along garment seams. While adjusting the underlying sewing patterns for maximized fit of wallpapers along seams, past research does not account for global symmetries that underlie almost every sewing pattern due to the symmetry of the human body. We propose an interactive tool to define such symmetries and integrate them into the existing algorithm, such that both the texture alignment and the deformation of the sewing pattern adhere to these symmetries.

1. Introduction

Customizing products to individual needs has become a trend capturing many industry domains, including 3D printed objects, custom prints on products or fashion design. This has spawned interest in computational design tools enabling even inexperienced users to manipulate an initial design or create new ones. Garments are commonly created from several planar cloth pieces sewn together to form the desired shape. The process of creating a sewing pattern for a design requires extensive experience, since the placement of seams can impact visual appearance and physical behaviour of the garment. Especially the use of textured fabric with repeating patterns can unintentionally reveal seams due to discontinuities in the

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motif, since the human eye is excellent at detecting pattern breaks. It is therefore a challenge to position sewing pattern pieces of a given garment design on the fabric such that these discontinuities disappear. In industry, this tedious task is done by hand and only for high-end clothes, by experienced tailors. Recent work by Wolff and Sorkine-Hornung [WS19] introduces a method to tackle this problem automatically. Given an initial sewing pattern and a repetitive textile print (also called a wallpaper), their algorithm optimizes wallpaper alignment and the sewing pattern shape in order to maximize fit of the wallpaper across seams. One important aesthetic feature not considered in their approach is the reflection symmetry of certain sewing pattern pieces, mostly due to the main symmetry axis of the human body. In the following, we refer to these as *global symmetries* to differentiate them from symmetries in the wallpaper or symmetries in the alignment along seams.

In this work, we extend the above algorithm such that we do not only optimize a design for fit across seams but also enforce global symmetry constraints. In many cases garments are symmetric; after all, the human body exhibits reflection symmetry with respect to the sagittal plane. Small imperfections in symmetry of any human body are ignored by all sewing pattern designs that are not custom-fitted to a specific person. Our goal is to ensure that the global symmetry of the sewing pattern shape is not broken during optimization and is respected in the alignment of the texture pattern. Our approach is flexible enough to incorporate reflection symmetry of arbitrary orientation as well. Our focus on this global symmetry results in two different types of symmetries that need to be considered: reflection symmetry of a single pattern piece and symmetry of two pieces. The former appears for example in the front of shirts or dresses (see Fig. 1, where every single pattern piece of the initial sewing pattern exhibits a global reflection symmetry). Most sleeves exhibit the second type of symmetry (see the sleeves of the blue shirt or all pieces of the red shirt in Fig. 9). Either one or a combination of both types can occur in a garment, together with parts that are not globally symmetric (see the green dress in Fig. 9). Both types of symmetry mostly appear in sewing patterns due to the reflection symmetry of the human body, but this is not always the case. Therefore we allow the user to interactively define symmetries, simply by clicking the corresponding sewing pattern pieces. We then obey the desired global symmetry constraints while aligning the wallpaper as well as changing the sewing pattern shape. For this task, most aspects of the algorithm of Wolff and Sorkine-Hornung must be modified, as described in Sec. 3. After discussing related work in the areas of computational garment design and symmetry based geometry processing, we revisit the approach of Wolff and Sorkine-Hornung [WS19] in more detail.

2. Related work

Garment design. Over the years there has been some research in computational garment design in different scientific fields, some of which is reviewed in a survey by Nayak and Padhye [NP17]. Many works focus on the interactive design and modification of sewing patterns with visual realtime feedback [KFW04; VCM05] allowing the exploration of design choices, which would be time and cost intensive otherwise. Inspired by the traditional technique of sketching the shape of garments to explore novel designs, another line of research incorporates sketching as a basic input paradigm for garment design [DJW*06; TWB*07; RSW*07; RMSC11]. Recently, machine learning has been employed to deduce garment shapes from sketches [WCPM18]. Other works rely on existing sewing patterns and customize them to different needs, like specific body shapes [BSBC12], or allowing for a combination of patterns [BSK*16].

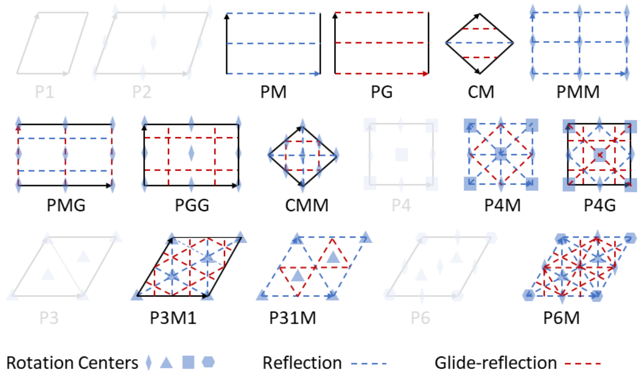

Figure 2: *All 17 wallpaper groups can be characterized by primitive cells generating the repetitive patterns. The greyed out patterns do not exhibit any reflection or glide-reflection symmetries and therefore cannot be used for fulfilling our global symmetric constraints. The groups PG and PGG only possess glide reflection axes, which makes them suitable only for global symmetry between two distinct sewing pattern pieces.*

Symmetry. Our method exploits symmetry groups of repetitive 2D patterns. Fedorov [Fed91] exhaustively categorized all possible symmetries of these patterns in 17 so-called wallpaper groups (cf. Fig. 2). These groups classify all two dimensional repeating patterns and thus cover many fabrics. Fedorov considers symmetry with respect to translation, rotation, reflection and glide reflection, which is a reflection combined with a translation along the reflection axis. In Sec. 3 we analyze which wallpaper groups are suitable for fulfilling global symmetry constraints.

The survey of Mitra et al. [MPWC13] gives an overview on methods concerned with symmetry in geometry processing. Mitra et al. [MGP06] present methods to detect symmetries in surface meshes based on sampling pairs of points with similar signatures. Clustering these points detects partial symmetries in the shape. Mitra et al. [MGP07] use this method to enhance approximate symmetries in the shape, leading to globally symmetric shapes, while Gal et al. [GSMC09] employ similar ideas to enable symmetry aware object manipulation. Our algorithm is similar in spirit, since we also try to maintain symmetries present in the initial layout.

Rotation symmetries also play a central role in meshing. A quad mesh can be constructed from a rotational symmetry field of order 4 (4-RoSy) on a surface. Rotational symmetries of various orders appear in wallpapers. By employing ideas from the work of Jakob et al. [JTPS15] on the optimization of frame fields for quad meshing, the work by Wolff and Sorkine-Hornung [WS19] optimizes alignment of wallpapers along garment seams. To our knowledge, sewing pattern symmetry with respect to textured fabric has not

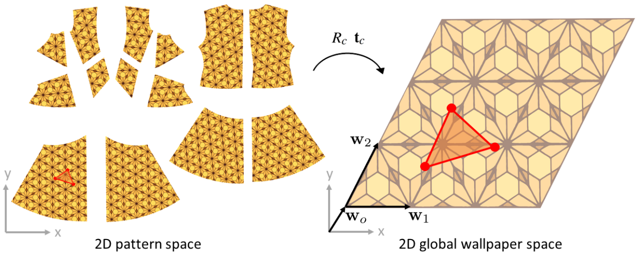

Figure 3: *Illustration of the connection between the 2D sewing pattern space and the 2D wallpaper space. For each piece P_c of the sewing pattern, a rotation R_c and a translation $\mathbf{t}_c$ are defined to map the vertices of the sewing pattern onto the wallpaper. Reprinted with permission from [WS19].*

been considered in the field of computational garment design, even though it constitutes a central aesthetic feature.

Wolff and Sorkine-Hornung. Our method builds on previous work by Wolff and Sorkine-Hornung [WS19]. Starting from an input garment, sewing pattern and wallpaper, their method strives to optimize the alignment of the wallpaper for each sewing pattern piece and minimally adjusts the sewing pattern shape to increase texture fit along seams, taking intrinsic symmetries of the 17 wallpaper groups into account. They consider both pattern continuity and pattern symmetry along seams as a good fit. We present the basic ideas of this algorithm here and then propose our extension by incorporating global symmetry constraints in Sec. 3.

The method of [WS19] proceeds in two steps. It first optimizes the wallpaper alignment for all sewing pattern pieces. To this end, the fabric's texture is represented as a tiling of the plane using the primitive cell spanned by two directions $\mathbf{w}_1$ and $\mathbf{w}_2$ of a specific wallpaper pattern (see Fig. 2 and 3). Each sewing pattern piece P_c is rigidly moved in this wallpaper space according to a rotation R_c, represented as the direction $\mathbf{r}_c = R_c^\top \mathbf{w}_1$ and a translation $\mathbf{t}_c$ (see Fig. 3). Rotations are optimized first in the spirit of Jakob et al. [JTPS15] in an iterative procedure looping over all pairs of seam edges of a piece P_c and averaging neighbouring rotations. More specifically, for an edge e of piece P_c, they identify its twin edge e' and find the smallest rotation of the current piece's wallpaper that aligns them in 3D modulo pattern symmetries. This rotation can be represented as the 2D correction vector $\mathbf{r}_e$, which is used to update the piece rotation:

$$\begin{aligned}\mathbf{r}_c &\leftarrow \mathbf{r}_c + w_e \mathbf{r}_e,\\ \mathbf{r}_c &\leftarrow \mathbf{r}_c / \|\mathbf{r}_c\|,\end{aligned} \tag{1}$$

where w_e is an edge weight comprised of a seam weight and the edge length. These local iterations minimize an energy defined on the sewing pattern pieces. They resemble the Gauss-Seidel method and achieve better convergence thanks to recomputing rotations after visiting each neighboring pattern piece, as described in [JTPS15]. More details, including how to incorporate reflection symmetry at seam lines are covered in [WS19]. After optimal rotations for all pieces have been found, translations are optimized in a similar manner, following the idea of a guiding orientation field to compute positions and sidestepping the need for a global optimization [JTPS15].

This procedure can already improve the fit significantly. But the human eye can detect even small pattern breaks easily and therefore, in a second step, the wallpaper fit is further improved by altering the sewing pattern shape. First, pairs of connected seam lines S_1 and S_2 between two pieces are considered in isolation and ideal seam lines are computed for both, such that the wallpaper fits perfectly. In a second step, these ideal but disconnected seam lines are approximated by deforming the sewing pattern pieces.

To calculate the ideal seam lines, S_2 is first transported to the parameterization space of S_1, in a manner that moves S_2 as close as possible to S_1, yielding a new seam line S_1^*, exploiting both translation, rotation and reflection symmetries of the wallpaper. By doing so, S_1^* lies on equivalent wallpaper points as S_2 and constitutes a possible ideal seam line replacing S_1 while keeping S_2 fixed. If S_1^* and S_1 are identical, the match is perfect and no further work is required. Since this is usually not the case, seam lines S_1 and S_1^* can be rigidly aligned using Procrustes, and S_2 is adjusted accordingly, resulting in the desired ideal seam lines.

Since all seam lines have been slightly modified individually in order to match their counterparts, they might not connect with the other seam lines of their sewing pattern piece. Therefore, in a last step, each pattern piece is deformed in order to approximate the new seam lines. This is achieved by minimizing a deformation energy comprised of four parts:

$$E_{\text{pattern}} = E_{\text{prox}} + \alpha\, E_{\text{conf}} + \beta\, E_{\text{flip}} + \gamma\, E_{\text{match}}, \tag{2}$$

where E_{prox} measures how close the seam lines are to the ideal ones, E_{conf} is the conformal deformation energy of the pattern pieces, E_{flip} prevents flipped triangles and E_{match} enforces edge pairs to maintain the same length. The last term ensures that all seams of the sewing pattern can be sewn and therefore one has to ensure that E_{match} is zero or at least very close to it. The quadratic penalty method is employed, which increases the parameter γ during the optimization, to achieve this goal.

3. Method

With these basics in place, we characterize the types of symmetry we are interested in and how they can be realized in addition to wallpaper alignment along seams. As described above, the global reflection symmetry of the human body leads to two types of symmetry that need to be addressed: reflection symmetry of a single sewing pattern piece and symmetry of two pieces. We discuss these separately for the wallpaper alignment step and then show how to alter the ideal seam line calculation and energy minimization jointly.

3.1. Reflection symmetry of a single piece

In case of a single piece, like the front part of a shirt, we allow the user to select two symmetric seam lines of that piece and use them to automatically calculate the reflection axis. We first reflect one of the two seams along an arbitrary axis. Then both seams can be put into correspondence by a rigid transformation, i.e., a rotation and a translation. We use the iterative closest points method

(ICP) [BM92] to find a rigid transformation to align both seams. Based on this alignment we can deduce the reflection axis by analyzing the reflection and rigid transformation. Alternatively, the user can directly define a symmetry axis by selecting a pair of points on the pattern piece. In Fig. 1 (a) the user selects pairs of seam lines (left and right) for each part, from which the symmetry axis is determined. Note that the symmetry axis does not necessarily align with the $y-$axis.

Having established the axis of symmetry, we can only satisfy this constraint by aligning the reflection axis of the pattern piece with a reflection axis of the wallpaper. Note that not all wallpaper groups contain a reflection symmetry, and thus our algorithm has to be limited to a subset of patterns. These are: PM, CM, PMM, PMG, CMM, P4M, P4G, P3M1, P31M, P6M (10 out of 17), as detailed in Fig. 2.

We augment the method of Wolff and Sorkine-Hornung [WS19] outlined above by constraining the rotation and translation to respect the desired symmetry. First, after updating the rotation of a pattern piece P_c for all its edges according to Eq. (1), we add a single simple step of adjusting the rotation, such that the reflection axis of the pattern piece aligns with the closest reflection axis of the wallpaper. This update depends on the wallpaper group, since each wallpaper contains a different set of reflection symmetries (see Fig. 4).

The previous step finds a good fit in terms of orientation across seams while perfectly aligning a wallpaper symmetry axis with the desired reflection symmetry axis on the garment. We can now similarly augment the update procedure for the translation by adjusting the translation vectors $\mathbf{t}_c$ after each completed update for one pattern piece P_c. We add an additional minimal translation $\mathbf{t}_c + \mathbf{t}_{c,\varepsilon}$ such that a reflection axis of the wallpaper aligns with the reflection axis of the pattern piece.

3.2. Symmetry of two pieces

The second type of symmetry concerns two pieces of the garment. We allow the user to simply click on two corresponding sewing pattern pieces to define symmetry between them. Since we now work with two sewing pattern pieces, we can also use wallpapers possessing only glide reflections, in contrast to the single piece case, since we can simply translate the wallpaper accordingly in one of the two pieces. This property adds PG and PGG to the set of admissible wallpaper patterns for two-piece symmetry and leads to a total of 12 usable wallpaper groups (see Fig. 2).

Even though designers often choose to place symmetric pattern pieces with respect to a reflection axis in the 2D plane, this is not necessarily the case and a simple reflection axis might not exist. However, the positioning of the two symmetric pieces is always coupled via a reflection F about an arbitrarily chosen axis and a rigid transformation $(R_{sym,c},\ \mathbf{t}_{sym,c})$ (see Fig. 5). We again use ICP to calculate this rigid transformation. A pair of corresponding points $\mathbf{p}$ and $\mathbf{p}'$ is related by the equation

$$\mathbf{p}' = R_{sym,c}\, F\mathbf{p} + \mathbf{t}_{sym,c}. \tag{3}$$

Since we can choose the reflection axis of F arbitrarily, we always set F to be a reflection about the y-axis. Each of the two sewing

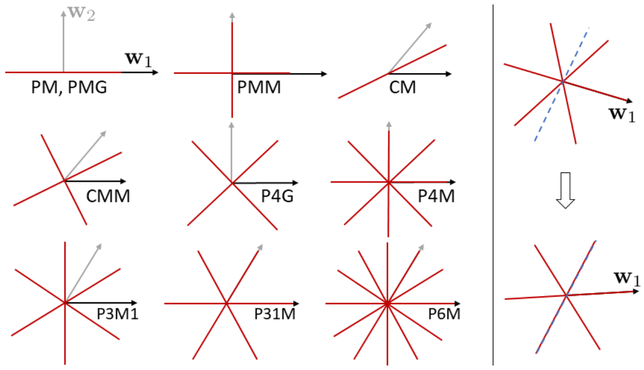

Figure 4: *Reflection axes of different wallpaper patterns: On the left we show all wallpapers containing a reflection axis. For each, we show the orientation of all reflection axes with respect to the wallpapers' translation vectors $\mathbf{w}_1$ and $\mathbf{w}_2$ in red. Note that for most wallpapers the angle of the reflection axes is fixed (0, 30, 45, 60, 90, 120, 135 and 150 degree). Only for CM and CMM the angle depends on the angle between $\mathbf{w}_1$ and $\mathbf{w}_2$. On the right we show how the rotation of the wallpaper $\mathbf{r}_c$ (depicted as the rotation of $\mathbf{w}_1$) can be aligned with the reflection axis (blue) of the sewing pattern piece P_c.*

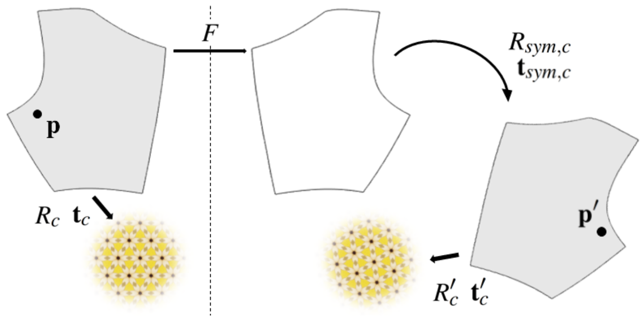

Figure 5: *The coupling of the positions of two symmetric sewing pattern pieces (grey) through a reflection F, a rotation $R_{sym,c}$ and translation $\mathbf{t}_{sym,c}$. The wallpaper alignment for each piece is given by the transformations $(R_c, \mathbf{t}_c)$ and $(R'_c, \mathbf{t}'_c)$.*

pattern pieces has a wallpaper alignment defined by the transformations $(R_c, \mathbf{t}_c)$ and $(R'_c, \mathbf{t}'_c)$ (see Fig. 5). Since we desire a symmetric wallpaper alignment, we need to link these transformations in a way that maps the points $\mathbf{p}$ and $\mathbf{p}'$ to equivalent wallpaper points $\mathbf{p}^{wp} = R_c^{\mathsf{T}}(\mathbf{p} - \mathbf{t}_c)$ and $\mathbf{p}'^{wp} = R_c'^{\mathsf{T}}(\mathbf{p}' - \mathbf{t}'_c)$. Textiles in the garment industry usually have a front side with a print or desired weaving pattern and a backside without print or with an undesired pattern. Therefore we cannot turn a textured textile and cut one symmetric piece from the front and the other from the back to achieve symmetry of two pieces. We must instead rely on reflection symmetries of the wallpaper together with rotations and translations to mimic this flip. In Fig. 6 (a) we show a wallpaper without any reflection axis. No rotation and translation exists to imitate a reflection of this wallpaper. However, if a wallpaper possesses a reflection or glide-reflection axis like the one shown in Fig. 6 (b), we can rotate and

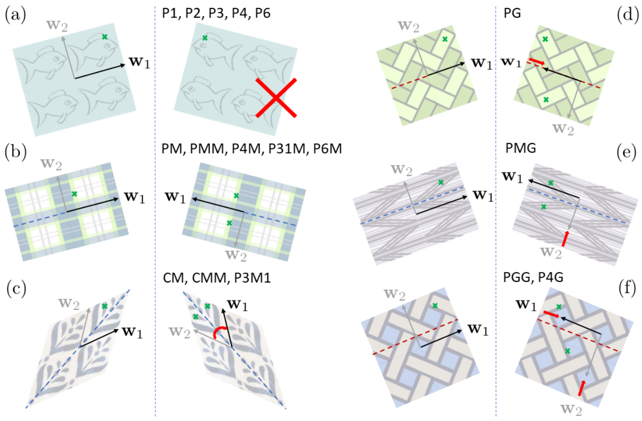

Figure 6: *We show how reflection along an axis can be handled for different wallpaper groups. For some, reflection cannot be achieved through rotation and translation of the wallpaper (a). Most wallpapers can be handled by reflecting the vector* $\mathbf{w}_1$ *about the defined symmetry axis (b), but many other wallpapers need special corrections (c-f). Small green crosses represent equivalent wallpaper points. On the right of each wallpaper example, two green crosses are shown: one positioned inside the wallpaper cell spanned by* $\mathbf{w}_1$ *and* $\mathbf{w}_2$ *just as the one on the left, and the second being a reflection of the one on the left.*

translate the reflection axis in such a way that the wallpaper appears to be reflected.

To understand how we can relate R'_c to R_c, we can view these rotations as the rotation of the main translation vector $\mathbf{w}_1$ of the wallpaper. Almost all of the suitable wallpapers (apart from CM, CMM and P3M1) possess a reflection or glide-reflection axis with the same direction as $\mathbf{w}_1$. We therefore set

$$R'_c = R_g\, R_{sym,c}\, R_\pi\, R_c^\top, \tag{4}$$

where R_π is a rotation by π and $R_\pi\, R_c^\top$ replaces the flip F, such that the vector $\mathbf{w}_1$ is reflected along the y-axis. The rotation $R_{sym,c}$ adjusts for the position of the second pattern piece in the 2D plane as shown in Fig. 5. Since the wallpapers CM, CMM, and P3M1 do not possess a reflection axis along $\mathbf{w}_1$, but instead have one along $\mathbf{w}_1 + \mathbf{w}_2$, we need a correction rotation for these wallpapers as illustrated in Fig. 6 (c) that depends on the wallpaper group g:

$$R_g = \begin{cases} \mathrm{rot}(\measuredangle(\mathbf{w}_1, \mathbf{w}_2)) & \text{for CM, CMM, C3M1,} \\ \mathbf{I}_{2\times 2} & \text{otherwise,} \end{cases} \tag{5}$$

where $\mathrm{rot}(\measuredangle(\mathbf{w}_1, \mathbf{w}_2))$ represents a rotation by the angle between $\mathbf{w}_1$ into $\mathbf{w}_2$.

We can understand the translations $\mathbf{t}_c$ and $\mathbf{t}'_c$ as the translation of the origin of the wallpaper space spanned by $\mathbf{w}_1$ and $\mathbf{w}_2$ and we can therefore set $\mathbf{t}'_c$ according to Eq. (3):

$$\mathbf{t}'_c = \mathbf{t}_g + R_{sym,c}\, F\, \mathbf{t}_c + \mathbf{t}_{sym,c}, \tag{6}$$

where $\mathbf{t}_g$ is a correction translation depending again on the wallpaper group g:

$$t_g = \frac{1}{2} R'_c \begin{cases} \mathbf{w}_1 & \text{for PG,} \\ \mathbf{w}_2 & \text{for PMG,} \\ \mathbf{w}_1 + \mathbf{w}_2 & \text{for PGG and P4G,} \\ (0,\ 0)^\top & \text{otherwise.} \end{cases} \tag{7}$$

Wallpapers PG and PGG only possess glide-reflection axes along $\mathbf{w}_1$, and we need to compensate for the gliding by adding half of it (Fig. 6 (d) and (f)). Wallpapers PMG and PGG possess (glide)-reflection axes that are by definition offset along the direction of $\mathbf{w}_2$ and we therefore need to add half of it (Fig. 6 (e) and (f)). As P4G possesses the same glide-reflection axes as PGG, we handle this wallpaper in the same way.

Having defined the relation of the transformations $(R_c, \mathbf{t}_c)$ and $(R'_c, \mathbf{t}'_c)$, we now effectively treat both pattern pieces as a single piece P_c with unified degrees of freedom. The actual optimization step proceeds according to Eq. (1) while taking the relation of some transformations into account. When considering the edges of a piece P_c and its symmetric counterpart P'_c, we only update R_c and $\mathbf{t}_c$. This is straightforward for seam edges of P_c and is done according to [WS19]. For seam edges of P'_c we use equations (4) and (6) to calculate R'_c and $\mathbf{t}'_c$ and then translate their update back to P_c.

3.3. Improved ideal seam lines

So far, we optimized wallpaper alignment for a better fit along seams while at the same time enforcing global symmetry constraints. However, as explained in [WS19], this is an overconstrained problem, even more so when introducing symmetry constraints, and we usually do not achieve a perfect fit. To alleviate this problem we can proceed by creating ideal seam lines and altering the sewing pattern accordingly to allow for a better fit as summarized in Sec. 2. We propose a modified variant of the procedure for creating ideal seam lines.

In the previous approach described above, ideal seam lines are created by exploiting pattern symmetries followed by rigid alignment using Procrustes analysis. This ensures a perfect wallpaper fit, however, the overall curvature of the seam is always exactly the curvature of S_2, independent of the shape of S_1. This is problematic when twin seam lines do not have the same curvature, as is usually the case for seams between sleeves and torso sewing pattern pieces (see the blue shirt in Fig. 9). In such cases, the shape of the resulting ideal seam lines depends on an arbitrary ordering of the pair S_1 and S_2. In cases where two seams are symmetric in the input sewing pattern, but each has twin seam lines with differing curvature (as the seams between the torso and the sleeves in the blue shirt in Fig. 9), the existing algorithm might not yield symmetric results (as shown in Fig. 8 left). Therefore, we propose to deform both seam line shapes towards an interpolation of both as an additional step before applying the existing algorithm rather than simply using rigid transformations of only one of them. We average the shape of both seam lines by simply averaging the angle between edges at each vertex consecutively (as illustrated in Fig. 7). Altering only angles has the advantage, that the overall length of the seam stays the same. The final position of seam lines after averaging angles depends on the order of the visited vertices. A final rigid alignment

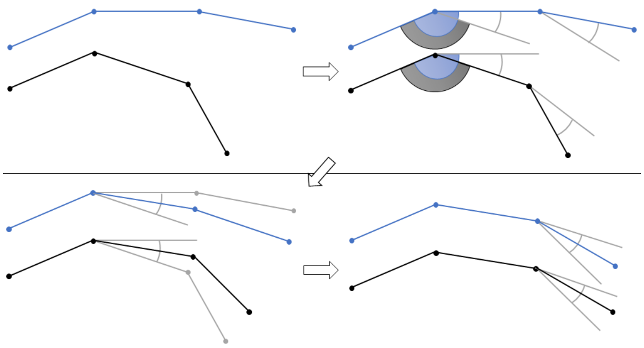

Figure 7: *We average two twin seam lines (blue and black) by consecutively averaging edge angles.*

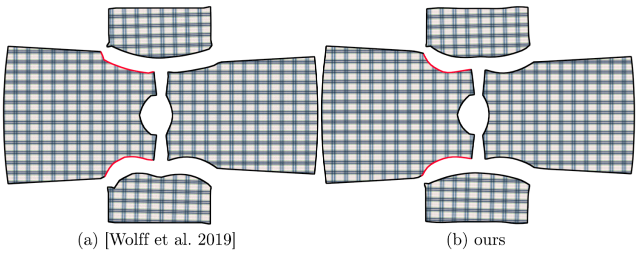

Figure 8: *We show the difference when simply averaging ideal seam line shapes (without using any symmetry constraints on the wallpaper alignment and sewing pattern shape optimization yet). While previous work (left) exhibits clearly visible asymmetries in the optimized sewing pattern in the seams connecting the sleeves to the garment, our altered approach (right) avoids these problems.*

with the original seam lines resolves this ambiguity. Afterwards, we can use the original procedure of [WS19] to create ideal seam lines. In Fig. 8 we show the difference between the old process and our altered process of creating ideal seam lines.

3.4. Symmetric sewing pattern optimization

Since we create ideal seam lines for each seam individually, they are possibly disconnected in a single sewing pattern piece. In this section we describe how to include global symmetry constraints in the energy minimization described in [WS19] that deforms the sewing pattern pieces towards the ideal seam lines. Even though symmetric sewing pattern pieces have a symmetric wallpaper alignment, we nevertheless do not automatically get symmetrically deformed pieces without incorporating symmetry constraints in the energy minimization. The reason is that symmetric sewing pattern pieces (or the two sides of a single symmetric piece) can border different asymmetric pieces with different wallpaper alignment, resulting in asymmetric ideal seam lines.

In Eq. (3), we define a correspondence between points of two sewing pattern pieces. We can equivalently define such a correspondence of points of a single pattern piece with a user defined reflection axis by $(R_{\mathrm{sym},c}, \mathbf{t}_{\mathrm{sym},c})$. We assume that boundaries are discretized consistently with respect to symmetries and each boundary vertex $\mathbf{b}_i$ has a corresponding vertex $\mathbf{b}'_i$ on the symmetric boundary. Input sewing patterns created with a professional software like CLO3D [CLO18] automatically fulfill this property, otherwise a straightforward remeshing step can enforce one-to-one correspondence. We introduce a new term E_{sym} to enforce vertices $\mathbf{b}_i$ and $\mathbf{b}'_i$ to stay symmetric as defined by Eq. (3) during the shape deformation. The energy can then be formulated as a sum over all boundary vertices that are part of sewing pattern pieces with a global symmetry:

$$E_{\mathrm{sym}} = \sum_i \|\mathbf{b}_i - (R_{\mathrm{sym},c}\, F\, \mathbf{b}'_i + \mathbf{t}_{\mathrm{sym},c})\|^2.$$

Enforcing this energy to be zero ensures that equivalent seams with respect to reflection symmetry stay symmetric. Since this is a soft constraint we add this energy to E_{match} in Eq. (2), yielding

$$E_{\mathrm{pattern}} = E_{\mathrm{prox}} + \alpha\, E_{\mathrm{conf}} + \beta\, E_{\mathrm{flip}} + \gamma\, (E_{\mathrm{match}} + E_{\mathrm{sym}}). \quad (8)$$

When optimizing the objective, the parameter γ is increased according to the quadratic penalty method in each iteration to enforce both constraints.

4. Results and discussion

We apply our algorithm to a set of different garments and wallpapers. All garment models in this paper are obtained from public sources. The yellow dress in Fig. 1 is provided with the work by Brouet et al. [BSBC12]. The red shirt and the green dress in Fig. 9 (the second being modified by us) are from the work by Li et al. [LSGV18]. The blue shirt in Fig. 9 is part of the Marvelous Designer Garment Library [Elv19]. All textures are either photographed or painted by us.

Figures 1 and 9 compare the results of our method to the previous work [WS19]. The left column shows the original sewing patterns along with user prescribed symmetry constraints, either as a symmetry line for single piece symmetry or corresponding letters for two-piece symmetries. Starting from an initial sewing pattern and wallpaper, both methods optimize for the fit along seams. However, without the additional global symmetries from our method, the optimized sewing patterns by Wolff and Sorkine-Hornung [WS19] are clearly not symmetric, and this asymmetry affects the 3D shape of the garment (especially visible in the yellow and green dresses) as well as the visual fit along seams (see the yellow and green dresses and the red shirt). Different sewing patterns also have an influence on how the garment falls under gravity.

Table 1 summarizes our results. Following Wolff and Sorkine-Hornung [WS19], we measure wallpaper fit as

$$E_{\mathrm{fit}} = \sum_{(e,e')\in\mathcal{S}} l_e\, d(\mathbf{v}_e),$$

where $\mathcal{S}$ is the set of seam edge pairs, l_e represents edge length ($l_e = l_{e'}$ for converged results) and $d(\mathbf{v}_e)$ measures the distance between the edge midpoints of e and e' in wallpaper space modulo pattern symmetries. When $d(\mathbf{v}_e) = 0$, it means that both edge midpoints are mapped to equivalent points and therefore provide a perfect fit. We also visualize the fit along seams in Figures 1 and 9. Enforcing symmetry leads to fewer degrees of freedom, and the values of E_{fit} are often higher for our method, as can be seen in Table 1. Nevertheless, the achieved symmetry still enhances the visual quality of the garment (see Fig. 1 and Fig. 9) and for a few examples (like the red shirt) our method even results in a smaller value for E_{fit}, which can be attributed to the advanced seam consolidation step described in Sec. 3.3.

In terms of performance the main bottleneck is the optimization of the energy (Eq. (8)). Our approach requires more iterations to converge compared to the original one due to the more complicated constraints, which results in a longer overall running time. All experiments have been conducted on a computer with a 1.2 GHz CPU and 64 GB memory.

Table 1: *Comparison of performance and quality measurements between our algorithm and previous work [WS19].*

	yellow dress	blue shirt	red shirt	green dress
number of triangles	16.5k	9k	5k	5k
E_{fit}, random [cm^2]	306.7	275.3	182.7	386.3
E_{fit}, previous [cm^2]	97.3	198.9	138.7	136.6
E_{fit}, ours [cm^2]	153.8	221.7	94.6	215.0
comp. time [*sec*], previous	27	30	4	15
comp. time [*sec*], ours	50	130	39	128
total iterations, previous	230	442	62	457
total iterations, ours	548	2688	1185	4520

5. Conclusions

We have shown how to incorporate the global symmetry of the human body, which is reflected in many sewing patterns, into the process of aligning wallpaper patterns along seams and the optimization of sewing pattern shapes. The resulting sewing patterns lead to garments with a much more refined look while still allowing for a good wallpaper fit across seams.

Limitations. Since we add more constraints to an already over-constrained problem, we also constrain the design space further. Some design choices, like the diagonal direction of stripes on the blue shirt (see Fig. 9, top middle), which leads to a good alignment along seams at the shoulders, are impossible when incorporating symmetry constraints.

Future work. In the future, we would like to incorporate existing work on symmetry detection as listed in Sec. 2 in order to automatically detect and incorporate sewing pattern symmetries, eliminating the need for user input. Improving the efficiency of the global sewing pattern optimization in Sec. 3.4 could lead to a much more interactive workflow, allowing the user to quickly iterate over different choices for symmetry constraints and weight parameters of the objective function. We would also like to explore the creation of tight packings of the sewing pattern pieces while respecting the texture alignment in order to reduce fabric waste.

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Figure 9: *For a given sewing pattern and wallpaper (a), we compare recent work by Wolff and Sorkine-Hornung [WS19] (b) with our altered approach (c). The mismatch $d(\mathbf{v}_e)$ at each seam edge is visualized on a color scale from green (0 cm) to red (2 cm).*

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