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Oriented mixed area and discrete minimal surfaces

Christian Müller and Johannes Wallner

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ORIENTED MIXED AREA AND DISCRETE MINIMAL SURFACES

CHRISTIAN MÜLLER AND JOHANNES WALLNER

ABSTRACT. Recently a curvature theory for polyhedral surfaces has been established which associates with each face a mean curvature value computed from areas and mixed areas of that face and its corresponding Gauss image face. Therefore a study of minimal surfaces requires studying pairs of polygons with vanishing mixed area. We show that the mixed area of two edgewise parallel polygons equals the mixed area of a derived polygon pair which has only the half number of vertices. Thus we are able to recursively characterize vanishing mixed area for hexagons and other n -gons in an incidence-geometric way. We use these geometric results for the construction of discrete minimal surfaces and a study of equilibrium forces in their edges, especially those with the combinatorics of a hexagonal mesh.

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1. INTRODUCTION

Minimal surfaces represent a prominent topic which has attracted great interest for a long time and which several times has been the object of significant new developments. They combine differential geometry with other fields, notably complex analysis. Also the recent field of *discrete differential geometry* has not neglected them, and indeed the present paper represents a contribution to this area. Before entering into details we want to say a few general words on the analogies and differences between the smooth and discrete categories.

The appeal of smooth minimal surface theory is to a large extent due to the fact that the same class of surfaces is characterized by different properties which are unrelated a priori, such as vanishing mean curvature, local surface minimization, or analyticity of isothermic parametrizations. Accordingly there is a variety of constructions of minimal surfaces: as solutions of Plateau's problem, as real part of Lie's sum of curves surfaces, or by Christoffel duality.

Transferring all these properties to the discrete category at the same time is not easy. Obviously we can pick a class of discrete surfaces (for instance, triangle meshes) and consider those discrete surfaces which enjoy a certain property analogous to one of the known properties of smooth minimal surfaces. However it is not guaranteed that these discrete minimal surfaces have any of the other properties which make their smooth counterparts such an interesting object of study. Nevertheless, for *some* appropriate discretizations this is exactly what happens, and it is a major aim in discrete differential geometry to find them.

The following constructions stand out: U. Pinkall and K. Polthier [5] considered the class of triangle meshes and defined minimality by surface minimization. The resulting discrete minimal surfaces are, among others, minimizers of Dirichlet energy, capable of discrete conjugate surfaces, and allow for the solution of a discrete Plateau's problem. A. Bobenko and U. Pinkall [2] studied discrete isothermic surface parametrizations (this means quadrilateral meshes with planar faces and a cross ratio condition for the vertices). This approach led to a discrete Christoffel duality for isothermic parametrizations, where minimal surfaces and spheres correspond to each other, just as in the smooth case. This viewpoint is assumed by several papers based on [2], e.g. [10]. A. Bobenko, T. Hoffmann, and B. Springborn [1] took the idea of Christoffel duality further and applied it to Koebe polyhedra. They constructed a circle-based class of discrete minimal surfaces which exhibits convergence to the smooth case and makes it possible to find minimal surfaces from the combinatorics of the network of principal curvature lines.

It turned out that the discrete curvature theory for polyhedral surfaces introduced by H. Pottmann et al. [6], which is based on the variation of surface area in offset surfaces, contains both [2] and [1] as special cases. Minimality of a polyhedral

surface with respect to an edgewise parallel Gauss image is in that context defined by vanishing mixed area of corresponding faces.

This brings us to the topic of the present paper, which systematically studies the vanishing mixed area property for polygons, having in mind as a main application the discrete minimal surfaces in the class of hexagonal meshes. After setting up the necessary definitions in the rest of this section, we continue with a geometric recursion for the computation of oriented mixed areas in Section 2. In Section 3 this leads to ways of characterizing pairs of parallel polygons whose mixed area is zero. Section 4 considers hexagonal meshes which are minimal and uses the incidence-geometric characterizations of vanishing mixed area which were obtained earlier for the construction of equilibrium forces in the edges of a minimal mesh.

1.1. Convex polygons and parallelity. For two convex subsets $K, L \subseteq \mathbb{R}^2$, the area of nonnegative Minkowski combinations $\lambda K + \mu L$ obeys the law

$$(1) \quad \text{area}(\lambda K + \mu L) = \lambda^2 \text{area}(K) + 2\lambda\mu \text{area}(K, L) + \mu^2 \text{area}(L),$$

where the symbol $\text{area}(K, L)$ means the *mixed area* of K and L (see for example [9]). If the boundary ∂K is a polygon P with vertices p_0, \dots, p_{N-1} , then the oriented area of K is given by Leibniz' sector formula

$$(2) \quad \text{area}(P) := \text{area}(K) = \frac{1}{2} \sum_{0 \leq i < N} \det(p_i, p_{i+1}).$$

Here indices are taken modulo N . Obviously, there is a vector space of polygons with N vertices, and the area functional (2) is a quadratic form in this space. For us, the most interesting case is that K and L are bounded by *parallel polygons* P and Q , with vertices p_0, \dots, p_{N-1} and q_0, \dots, q_{N-1} , respectively. This concept, which is not restricted to convex polygons, was introduced by [6] and means that

$$p_{i+1} - p_i, q_{i+1} - q_i \text{ are linearly dependent, for } i = 0, \dots, N - 1.$$

We assume for a moment that both P, Q have only nonzero edges (i.e., no coinciding vertices). Then the boundary $\partial(\lambda K + \mu L)$ has the vertices $(\lambda p_i + \mu q_i)_{0 \leq i < N}$, whence $\text{area}(\lambda K + \mu L) = \frac{1}{2} \sum_{0 \leq i < N} \det(\lambda p_i + \mu q_i, \lambda p_{i+1} + \mu q_{i+1})$ and consequently

$$(3) \quad \text{area}(P, Q) = \frac{1}{4} \sum_{0 \leq i < N} (\det(p_i, q_{i+1}) + \det(q_i, p_{i+1})).$$

This formula describes the symmetric bilinear form induced by the area functional in any vector space of polygons with N vertices.

If either P or Q has zero edges (i.e., multiple vertices), the vertices of $\partial(\lambda K + \mu L)$ need not equal $\lambda p_i + \mu q_i$, but if they do, (3) is valid.

Note that *arbitrary* polygons $\partial K, \partial L$ can be seen as parallel polygons, as illustrated by Figure 1: We are labeling the vertices r_0, \dots, r_{N-1} of $\partial(K + L)$ consecutively, and subsequently give (possibly multiple) indices p_0, \dots, p_{N-1} and q_0, \dots, q_{N-1} to the vertices of ∂K and ∂L such that $p_i + q_i = r_i$. Then all three boundaries of K ,

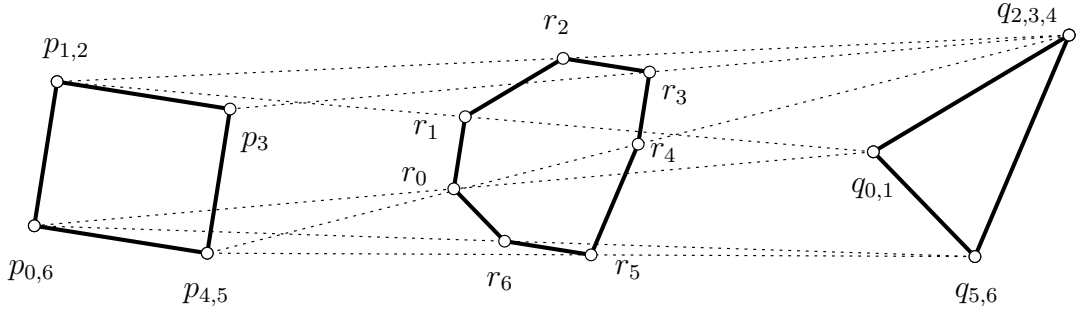


FIGURE 1. Labeling vertices of ∂K and ∂L with aid of $\partial(K + L)$ such that they become parallel.

L , $K + L$ and in fact $\lambda K + \mu L$ for $\lambda, \mu \geq 0$ are described by parallel polygons, and (3) can be used for computing the mixed area in the sense of (1).

1.2. The oriented mixed area. The polygons parallel to a given polygon $P = (p_0, \dots, p_{N-1})$, not necessarily convex, constitute a vector space under vertex-wise addition and scalar multiplication. Its dimension equals $N + \#\{i \mid p_i = p_{i+1}\}$. If there are no zero edges, we use the symbol

$$(4) \quad \mathcal{P}(P) = \{(q_0, \dots, q_{N-1}) \mid q_{i+1} - q_i = \lambda_i(p_{i+1} - p_i), 0 \leq i < N\} / \mathbb{R}^2$$

for the vector space of polygons parallel to P , modulo parallel translations. Then $\dim \mathcal{P}(P) = N - 2$. If both P and Q have zero edges, still $P + Q$ might not have, and consequently $P, Q, P + Q \in \mathcal{P}(P + Q)$. The expression defined by formula (3) is translation invariant. Following [6] we define:

Definition 1. For parallel polygons $P = (p_0, \dots, p_{N-1})$ and $Q = (q_0, \dots, q_{N-1})$, the oriented mixed area is given by the bilinear form (3).

Apparently the oriented mixed area, which extends the concept of mixed area for convex domains, is the bilinear form associated with the quadratic form measuring oriented area by Leibniz' sector formula.

1.3. Discrete minimal surfaces. The curvature theory presented in [6] deals with *parallel meshes*, which means a pair (Σ, Φ) of polyhedral surfaces having the same combinatorics, such that corresponding edges are parallel. Σ is viewed as Gauss image of Φ . The definition of parallelity of polygons extends to polygons which lie in parallel planes; in order to employ (3) for the computation of mixed area they have to be moved to a common plane by parallel translation. If P is a face and P' the corresponding face in the Gauss image, then P is assigned the mean and Gaussian curvatures

$$H_P = -\frac{\text{area}(P, P')}{\text{area}(P)}, \quad K_P = \frac{\text{area}(P')}{\text{area}(P)}.$$

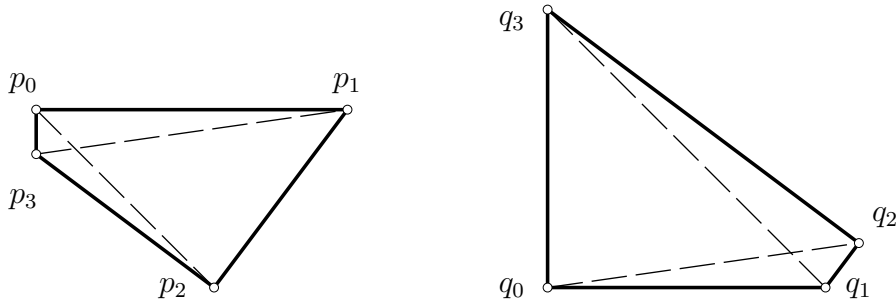


FIGURE 2. For nondegenerate parallel quads p_0, \dots, p_3 and q_0, \dots, q_3 , parallel of one nonzero diagonal characterizes vanishing mixed area ($q_0q_2 \parallel q_1q_3$, or $(q_1q_3 \parallel q_0q_2)$).

For this reason, *vanishing* mixed area of parallel polygons is characteristic for discrete minimal surfaces. The following result of [6], illustrated in Figure 2, is basic for the construction of minimal surfaces with regular quad mesh combinatorics:

Proposition 2. *Parallel quadrilaterals $P = (p_0, p_1, p_2, p_3)$ and $Q = (q_0, q_1, q_2, q_3)$ have vanishing mixed area if and only if diagonals p_0p_2 and q_1q_3 are parallel, which is equivalent to diagonals p_1p_3 and q_0q_2 being parallel.*

This condition actually discretizes the Christoffel duality between a minimal surface and its spherical Gauss image [6]. We therefore call a polyhedral surface and its parallel Gauss image where all mixed areas vanish, a *Christoffel dual pair*. It is an interesting fact that Proposition 2 applies to several constructions of discrete minimal surfaces based on quadrilaterals, namely the ones of [2, 1]. The present paper, which deals with vanishing mixed area in general, is focused on *hexagonal* meshes.

2. PROPERTIES OF THE ORIENTED MIXED AREA

The main result of the present paper is the recursion formula of Theorem 6 below, which for parallel polygons P, Q with an even number of vertices shows that $\text{area}(P, Q) = \text{area}(P^*, Q^*)$, where P^*, Q^* are derived polygons which have only the half number of vertices. It is used in Section 3 to derive geometric characterizations of parallel polygons with vanishing mixed area.

2.1. Formulas for the mixed area. There are equivalent formulae for the oriented mixed area of parallel polygons which take advantage of parallelity:

Lemma 3. *The bilinear form of Equation (3) is alternatively expressed as*

$$(5) \quad \sum_{i \in \{0, 1, \dots, N-1\}} \left(\det(p_i, q_{i+1}) + \det(q_i, p_{i+1}) \right) = \sum_{i \in \{0, 1, \dots, N-1\}} \det(p_i, q_{i+1} - q_{i-1})$$

(indices modulo N). For P, Q parallel and an even number of vertices,

$$(6) \quad 2 \operatorname{area}(P, Q) = \sum_{i \in \{0, 2, \dots, N-2\}} \det(p_i, q_{i+1} - q_{i-1}) = \sum_{i \in \{1, 3, \dots, N-1\}} \det(p_i, q_{i+1} - q_{i-1}).$$

PROOF. The first equality is found by rearranging indices:

$$\sum_i \det(p_i, q_{i+1}) + \sum_i \det(q_i, p_{i+1}) = \sum_i \det(p_i, q_{i+1}) + \sum_i \det(q_{i-1}, p_i).$$

In order to show the second equality, we observe that parallelity of P and Q implies $\det(p_{i+1} - p_i, q_{i+1} - q_i) = 0$. Therefore,

$$\begin{aligned} & \sum_{i \text{ even}} \det(p_i, q_{i+1} - q_{i-1}) = \sum_{i \text{ even}} (\det(p_i, q_{i+1} - q_i) + \det(p_i, q_i - q_{i-1})) \\ &= \sum_{i \text{ even}} (\det(p_i + (p_{i+1} - p_i), q_{i+1} - q_i) + \det(p_i + (p_{i-1} - p_i), q_i - q_{i-1})) \\ &= \sum_{i \text{ even}} (\det(p_{i+1}, q_{i+1} - q_i) + \det(p_{i-1}, q_i - q_{i-1})) \\ &= \sum_{i \text{ even}} (\det(p_{i+1}, q_{i+1} - q_i) + \det(p_{i+1}, q_{i+2} - q_{i+1})) \\ &= \sum_{i \text{ even}} \det(p_{i+1}, q_{i+2} - q_i) = \sum_{i \text{ odd}} \det(p_i, q_{i+1} - q_{i-1}). \end{aligned}$$

It follows that the expression for $4 \operatorname{area}(P, Q)$ according to (3) reads

$$\left(\sum_{i \text{ even}} + \sum_{i \text{ odd}} \right) \det(p_i, q_{i+1} - q_{i-1}) = \sum_{i \text{ even}} 2 \det(p_i, q_{i+1} - q_{i-1}),$$

which is what we wanted to prove. \square

We have now obtained an expression for the mixed area which makes use only of the vertices p_0, p_2, \dots and q_1, q_3, \dots , which however does not have a direct relation to the areas associated with polygons (p_0, p_2, \dots) and (q_1, q_3, \dots) .

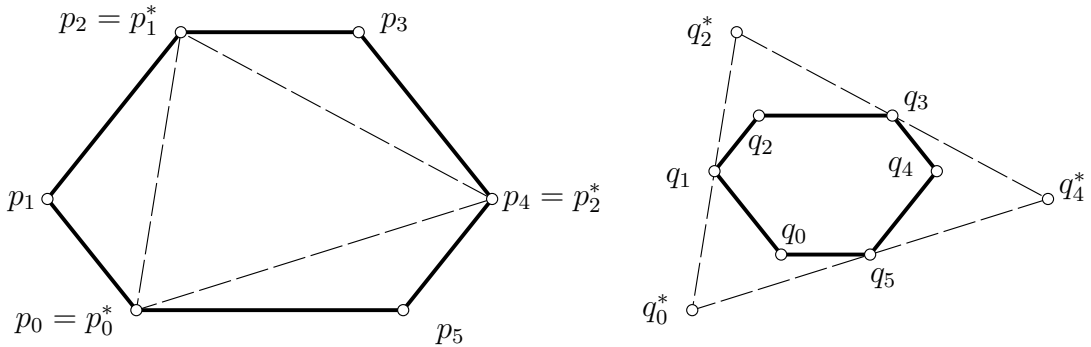


FIGURE 3. A pair of polygons P, Q and the derived polygons P^*, Q^* .

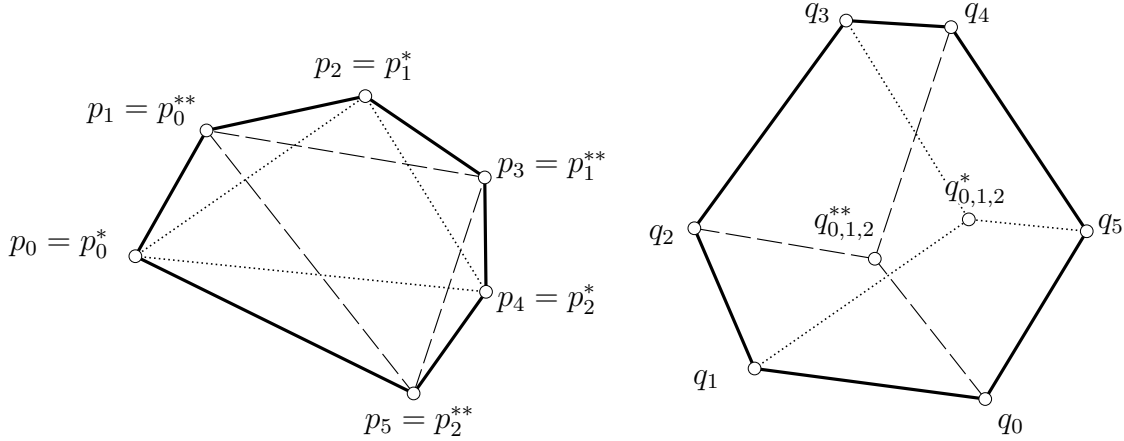


FIGURE 4. Illustration of Lemma 5. Polygons P^*, Q^* are orthogonal with respect to the bilinear form defined by the oriented are, if both derived polygons Q^* and Q^{**} degenerate into a point.

2.2. Construction of a derived polygon. For the following construction of derived polygons, the polygons P, Q must have an even number N of vertices, and certain diagonals of P are forbidden to be parallel. We used the notation $[v]$ for the 1-dimensional subspace spanned by the vector v .

Definition 4. Assume a pair of polygons $P = (p_0, \dots, p_{N-1})$ and $Q = (q_0, \dots, q_{N-1})$, where N is even, such that

$$(7) \quad p_i - p_{i-2} \text{ and } p_{i+2} - p_i \text{ are linearly independent for } i = 0, 2, 4, \dots$$

(indices are taken modulo N). Then a pair of derived polygons P^*, Q^* is constructed such that P^* consists of every other vertex of P , while the vertices of Q^* are found by parallel translating diagonals of P through points of Q :

$$(8) \quad p_i^* = p_{2i}, \quad q_i^* = (q_{2i+1} + [p_{2i+2} - p_{2i}]) \cap (q_{2i-1} + [p_{2i} - p_{2i-2}]).$$

An index shift of 1 yields an analogous derived pair (P^{**}, Q^{**}) based on the odd vertices of P : $p_i^{**} = p_{2i+1}$ and $q_i^{**} = (q_{2i+2} + [p_{2i+3} - p_{2i+1}]) \cap (q_{2i} + [p_{2i+1} - p_{2i-1}])$, provided the lines employed in this intersection are not parallel.

This construction is illustrated by Figures 3 and 4. Note that if Q^* cannot be constructed because (7) is not fulfilled, still Q^{**} may be constructible. For quadrilaterals, (7) is never fulfilled, even after an index shift. We will be able to treat quadrilaterals as degenerate hexagons.

2.3. Non-parallel polygons. The bilinear function of Equation (3) which measures the oriented mixed area for parallel polygons can be evaluated for arbitrary pairs of polygons, without having a geometric meaning as mixed area in the classical sense. It still extends the quadratic functional which measures the oriented

area by Leibniz' sector formula. The definition of derived polygons according to Definition 4 is not restricted to parallel polygons.

We here record a nice geometric property of this functional:

Lemma 5. *Polygons P, Q are orthogonal with respect to the bilinear function (3), if both derived polygons Q^* and Q^{**} with respect to even and odd indices degenerate into points q^* and q^{**} , respectively.*

PROOF. By Lemma 3, we have to show that $\sum_{0 \leq i < N} \det(p_i, q_{i+1} - q_{i-1}) = 0$. Our assumption on the degeneracy of derived polygons means that there are real numbers λ_i with

$$\begin{aligned} q^* &= q_i + \lambda_i(p_{i-1} - p_{i+1}) \text{ for } i \text{ even,} & q^{**} &= q_i + \lambda_i(p_{i-1} - p_{i+1}) \text{ for } i \text{ odd.} \\ \implies q_{i+1} - q_{i-1} &= \lambda_{i-1}(p_{i-2} - p_i) - \lambda_{i+1}(p_i - p_{i+2}) \text{ for all } i. \end{aligned}$$

We use this equality to evaluate (3):

$$\begin{aligned} & \sum_{0 \leq i < N} \det(p_i, q_{i+1} - q_{i-1}) \\ &= \sum_{0 \leq i < N} \det(p_i, \lambda_{i-1}(p_{i-2} - p_i) - \lambda_{i+1}(p_i - p_{i+2})) \\ &= \sum_{0 \leq i < N} \lambda_i \det(p_{i+1}, p_{i-1} - p_{i+1}) - \sum_{0 \leq i < N} \lambda_i \det(p_{i-1}, p_{i-1} - p_{i+1}) \\ &= \sum_{0 \leq i < N} \lambda_i \det(p_{i+1} - p_{i-1}, p_{i-1} - p_{i+1}) = 0 \end{aligned}$$

(indices are taken modulo N). This concludes the proof. \square

2.4. Mixed area of derived polygons. The following theorem is the main technical contribution of the present paper. It is the basis of geometric characterizations of polygons pairs with vanishing mixed area, and therefore the basis of constructions of discrete minimal surfaces.

Theorem 6. *For any pair of parallel polygons P, Q with an even number of vertices, the oriented mixed area is unaffected by the passage to derived polygons: $\text{area}(P, Q) = \text{area}(P^*, Q^*) = \text{area}(P^{**}, Q^{**})$, whenever the conditions of Definition 4, which allow construction of Q^* or Q^{**} , are fulfilled.*

PROOF. It is obviously sufficient to show the result for P^* and Q^* . An elementary computation yields the coordinates of Q^* 's vertices q_i^* :

$$\begin{aligned} q_i^* &= \frac{1}{\gamma_i} (\alpha_i(p_{i+1}^* - p_i^*) + \beta_i(p_i^* - p_{i-1}^*)), \quad \text{where} \\ \alpha_i &= \det(q_{2i-1}, p_i^* - p_{i-1}^*), \quad \beta_i = \det(p_{i+1}^* - p_i^*, q_{2i+1}), \\ \gamma_i &= \det(p_{i+1}^* - p_i^*, p_i^* - p_{i-1}^*). \end{aligned}$$

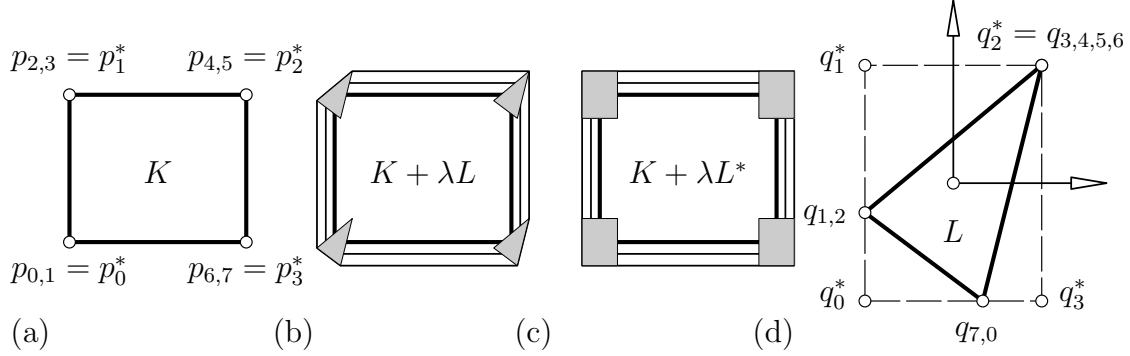


FIGURE 5. An explanation of the fact $\text{area}(P, Q) = \text{area}(P^*, Q^*)$ for artificially parallel polygons which occur as boundaries $P = \partial K$ and $Q = \partial L$. (a) Both polygons P and P^* describe the boundary ∂K . (b) Convex domains $K + \lambda L$, where λ equals 0.1 and 0.2. (c) The same for L^* instead of L , where the boundary ∂L^* is given by the polygon Q^* . (d) Polygons Q and Q^* . Obviously the linearly growing part of $\text{area}(K + \lambda L)$ along the edges of ∂K is not affected if we replace L by L^* .

We introduce the notation $\Delta_j^k = \det(p_j^*, p_k^*)$, which has the properties

$$\Delta_j^j = 0, \quad \Delta_i^j = -\Delta_j^i, \quad \gamma_i = \Delta_{i+1}^i - \Delta_{i+1}^{i-1} + \Delta_i^{i-1}.$$

For the mixed area of P^* and Q^* , we consider the following sum, where indices i range from 0 to $N/2 - 1$, and indices j range from 0 to $N - 1$:

$$\begin{aligned} & \sum_i \det(q_i^*, p_{i+1}^* - p_{i-1}^*) = \\ &= \sum_i \frac{1}{\gamma_i} \det(\alpha_i(p_{i+1}^* - p_i^*) + \beta_i(p_i^* - p_{i-1}^*), p_{i+1}^* - p_{i-1}^*) \\ &= \sum_i \frac{1}{\gamma_i} (\alpha_i(-\Delta_{i+1}^{i-1} - \Delta_i^{i+1} + \Delta_i^{i-1}) + \beta_i(\Delta_i^{i+1} - \Delta_i^{i-1} - \Delta_{i-1}^{i+1})) \\ &= \sum_i \frac{1}{\gamma_i} (\alpha_i \gamma_i - \beta_i \gamma_i) = \sum_i (\det(q_{2i-1}, p_i^* - p_{i-1}^*) - \det(p_{i+1}^* - p_i^*, q_{2i+1})) \\ &= \sum_{j \text{ even}} (\det(q_{j-1}, p_j - p_{j-2}) + \det(q_{j+1}, p_{j+2} - p_j)). \end{aligned}$$

An index shift shows that $\sum_{j \text{ even}} \det(q_{j-1}, p_j - p_{j-2}) = \sum_{j \text{ even}} \det(q_{j+1}, p_{j+2} - p_j) = \sum_{j \text{ odd}} \det(q_j, p_{j+1} - p_{j-1})$, so we conclude that

$$\text{area}(P^*, Q^*) = \frac{1}{4} \sum_i \det(q_i^*, p_{i+1}^* - p_{i-1}^*) = \frac{1}{2} \sum_{j \text{ odd}} \det(q_j, p_{j+1} - p_{j-1}).$$

By Lemma 3, this expression equals $\text{area}(P, Q)$, which concludes the proof. \square

This result concerning the mixed area of parallel polygons is strong in reducing the number of vertices to deal with by a factor 2. However, if we apply it to two arbitrary polygons, which are made artificially parallel like those of Figure 1, we only obtain a fact which is obvious from the definition of mixed area anyway. As illustrated by Figure 5, Q^* then describes the boundary of the domain L^* constructed from K and L as the intersection of all supporting half-spaces of L whose boundary is parallel to an edge of K . Obviously, $\text{area}(K, L) = \text{area}(K, L^*)$.

3. VANISHING MIXED AREAS

This section applies Theorem 6 to parallel polygons P, Q whose mixed area *vanishes*. As mentioned in § 1.3, such pairs of polygons are especially interesting for the construction of discrete minimal surfaces.

3.1. Vanishing mixed area for parallel hexagons. Here we treat both quadrilaterals and 5-gons as special hexagons. Before we derive a geometric criterion for the vanishing of mixed area for parallel hexagons, we discuss pairs P, Q of hexagons where Theorem 6 cannot be applied, because neither derived polygon Q^*, Q^{**} can be constructed. Obviously, this is the case if and only if both p_0, p_2, p_4 and p_1, p_3, p_5 are collinear, i.e., P is a Pappos hexagon (see Figure 6). Exchanging the role of P and Q helps, except for the case that both q_0, q_2, q_4 and q_1, q_3, q_5 are collinear.

Theorem 7. *For parallel hexagons P, Q where one, say P , is not a Pappos hexagon, there is a labeling of vertices such that the derived polygons P^*, Q^* can be constructed. Then $\text{area}(P, Q) = 0$ if and only if all vertices of the triangle Q^* coincide, i.e., if the lines*

$$q_1 + [p_2 - p_0], \quad q_3 + [p_4 - p_2], \quad q_5 + [p_0 - p_4]$$

intersect in a common point.

PROOF. The derived polygons P^*, Q^* are parallel triangles, with $Q^* = \lambda P^* + a$. It follows that $\text{area}(P^*, Q^*) = \lambda \text{area}(P^*)$. By non-collinearity of P^* , this area vanishes if and only if $\lambda = 0$. \square

The case of two Pappos hexagons has to be treated separately:

Proposition 8. *Suppose that P, Q are two parallel hexagons such that p_1, p_3, p_5 as well as q_0, q_2, q_4 are collinear (this includes the case of parallel Pappos hexagons). Then $\text{area}(P, Q) = 0$ in exactly the following cases:*

- (i) $p_1 = p_3 = p_5$ or $q_0 = q_2 = q_4$.
- (ii) The triples (p_1, p_3, p_5) and (q_4, q_0, q_2) are affinely equivalent.
- (iii) The lines which carry p_1, p_3, p_5 and q_0, q_2, q_4 are parallel.

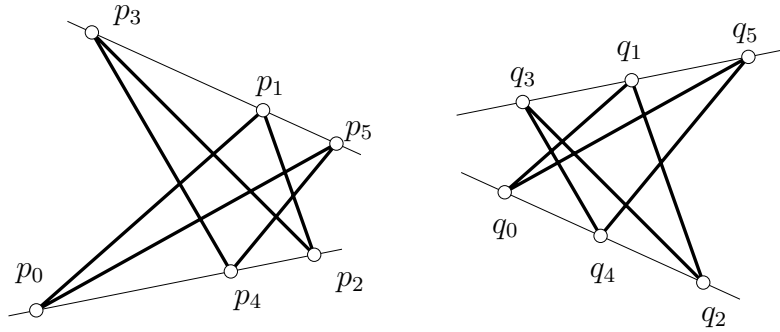


FIGURE 6. A Pappos hexagon does not fulfill the requirements of Definition 4, and so Theorem 7 is not applicable to this pair of parallel Pappos hexagons with $\text{area}(P, Q) = 0$ (we must apply Proposition 8 instead).

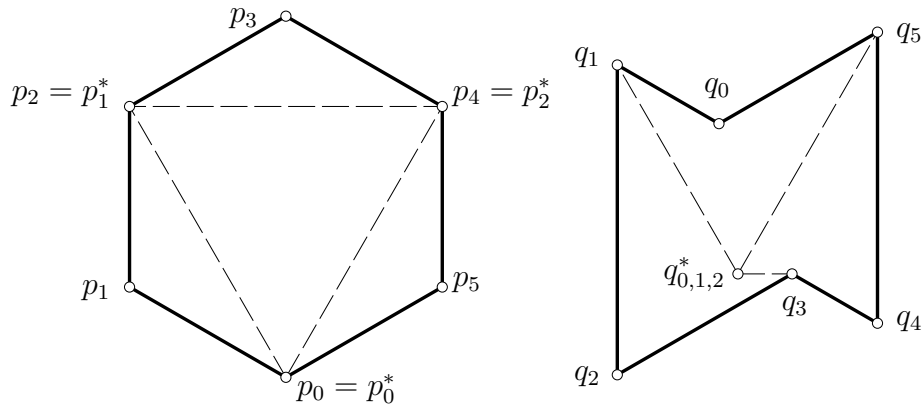


FIGURE 7. Parallel hexagons P, Q with vanishing mixed area (the derived triangle Q^* degenerates).

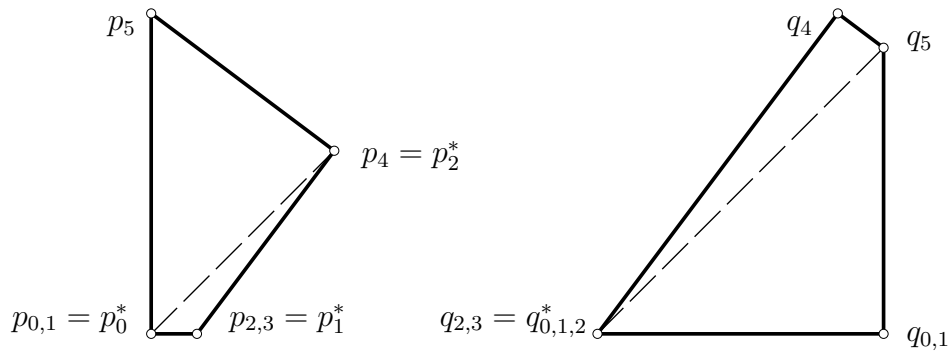


FIGURE 8. Quadrilaterals with antiparallel diagonals are degenerate hexagons P, Q , where the triangle Q^* degenerates into a point.

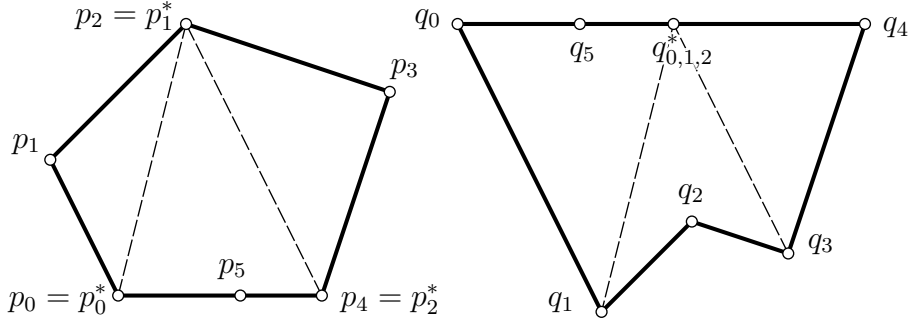


FIGURE 9. A pair of parallel 5-gons P, Q seen as hexagons, and a geometric characterization of vanishing mixed area which follows from this interpretation. Index shifts produce equivalent configurations.

PROOF. By parallel translation we can achieve that the straight lines pass through the origin of the coordinate system, so there are $v, w \in \mathbb{R}^2 \setminus 0$ with $p_i = \lambda_i v$ for $i = 1, 3, 5$ and $q_j = \mu_j w$ for $j = 0, 2, 4$. By Equation (5),

$$\begin{aligned} 2 \operatorname{area}(P, Q) &= \sum_{i=1,3,5} \det(\lambda_i v, (\mu_{i+1} - \mu_{i-1}) w) \\ &= \det(v, w) (\lambda_1 (\mu_2 - \mu_0) + \lambda_3 (\mu_4 - \mu_2) + \lambda_5 (\mu_0 - \mu_4)) \\ &= \det(v, w) ((\lambda_1 - \lambda_3) (\mu_2 - \mu_4) - (\lambda_1 - \lambda_5) (\mu_0 - \mu_4)) \end{aligned}$$

In case (iii) we have $\det(v, w) = 0$, so $\operatorname{area}(P, Q) = 0$. In case (i) we have $\lambda_1 = \lambda_3 = \lambda_5$, or $\mu_0 = \mu_2 = \mu_4$, which likewise implies vanishing mixed area. We now assume that we have neither case (i) nor case (iii). Then

$$\operatorname{area}(P, Q) = 0 \iff (\lambda_1 - \lambda_3) : (\lambda_1 - \lambda_5) = (\mu_4 - \mu_0) : (\mu_4 - \mu_2),$$

i.e., if and only if the ratio of collinear points p_1, p_3, p_5 equals the ratio of collinear points q_4, q_0, q_2 . This is equivalent to (ii). \square

We refrain from an exhaustive discussion of cases. An example of two parallel Pappos hexagons with vanishing mixed area is shown by Figure 6.

3.2. Vanishing mixed area for 4- and 5-gons as degenerate 6-gons. Two parallel *quadrilaterals* are converted to parallel hexagons if we count two pairs of corresponding vertices twice. This operation does not change the mixed area, and Theorem 7 immediately gives the known result of Proposition 2 that vanishing mixed area is characterized by anti-parallelity of diagonals (see Figures 2 and 8). Anyway Proposition 2 follows directly from Lemma 3, because for parallel quads, (6) expands to $\operatorname{area}(P, Q) = \det(p_0 - p_2, q_1 - q_3)$. For 5-gons, we have the following result:

Corollary 9. *The oriented mixed area of two parallel 5-gons $P = (p_0, \dots, p_4)$ and $Q = (q_0, \dots, q_4)$ vanishes if both of them are contained in a straight line. If this is*

not the case, $\text{area}(P, Q) = 0$ is characterized by the following geometric condition for one index i (and equivalently for all indices i): The lines

$$q_{i+1} + [p_{i+2} - p_i] \quad \text{and} \quad q_{i+3} + [p_{i+4} - p_{i+2}]$$

meet on the edge $q_{i+4}q_i$, where indices are taken modulo 5.

PROOF. It is sufficient to assume that p_0, p_1, p_4 are not collinear and show the result for the case $i = 0$ illustrated by Figure 9. By introducing vertices p_5, q_5 in the edges p_4p_0 and q_4q_0 , resp., we convert both P and Q into parallel hexagons, and Theorem 7 is applicable. The statement that Q^* degenerates to a point translates to the statement we want to show. \square

3.3. Vanishing mixed area for 8-, 7- and 6-gons (again). Theorem 6 is recursively applicable, but the number of cases to be distinguished because diagonals are parallel and derived polygons cannot be constructed becomes greater. The following result for generic 8-gons follows directly from Theorem 6 and Proposition 2 (see Figure 10).

Corollary 10. *Parallel 8-gons P, Q where the derived polygons P^*, Q^* can be constructed have vanishing mixed area exactly in the following three cases: (i) both sets $\{p_0, p_2, p_4, p_6\}$ and $\{q_0^*, q_1^*, q_2^*, q_3^*\}$ are contained in a straight line; (ii) $p_0 \neq p_4$ and p_0p_4 is parallel to $q_1^*p_3^*$, (iii) $p_2 \neq p_6$ and p_2p_6 is parallel to $q_0^*p_2^*$.*

The obvious way to treat parallel 7-gons is as 8-gons with two coincident vertices: We simply add an 8th vertex $p_7 = p_6$ and $q_7 = q_6$ to each and apply Corollary 10. This is illustrated by Figure 11. It is interesting to observe that also for hexagons we get again an easy geometric condition if we treat them as 8-gons with 2 coincident vertices (see Figure 12). Disregarding special cases, we have:

Corollary 11. *The parallel hexagons $(p_0, p_1, p_2, p_4, p_5, p_6)$ and $(q_0, q_1, q_2, q_4, q_5, q_6)$ generically have zero oriented mixed area if and only if $p_0 \vee p_4 \parallel q_1^* \vee q_3^*$, where*

$$q_1^* = (q_1 + [p_2 - p_0]) \cap (q_2 \vee q_4), \quad q_3^* = (q_5 + [p_4 - p_6]) \cap (q_6 \vee q_0).$$

PROOF. The polygons are extended to 8-gons P, Q with the same mixed area by letting $p_3 := p_2, p_7 := p_6, q_3 := q_2$, and $q_7 := q_6$. The derived quadrilateral Q^* according to Corollary 10 has the two vertices q_1^*, q_3^* , so the result follows. \square

4. DISCRETE MINIMAL SURFACES

Section 1.3 already introduced in general terms the definitions of curvature according to [6]. Recall that a polyhedral surface Φ is a discrete minimal surface with respect to a Gauss image Σ , if Φ, Σ are parallel meshes such that corresponding faces have vanishing mixed area. We view Φ as a discrete Christoffel dual of Σ , and vice versa.

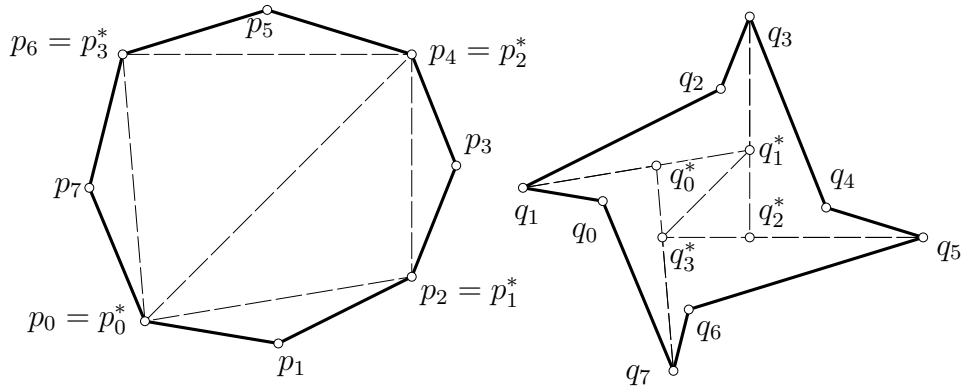


FIGURE 10. Parallel 8-gons P, Q with vanishing mixed area. The derived polygons P^*, Q^* are parallel quads with $\text{area}(P^*, Q^*) = 0$ and consequently antiparallel diagonals.

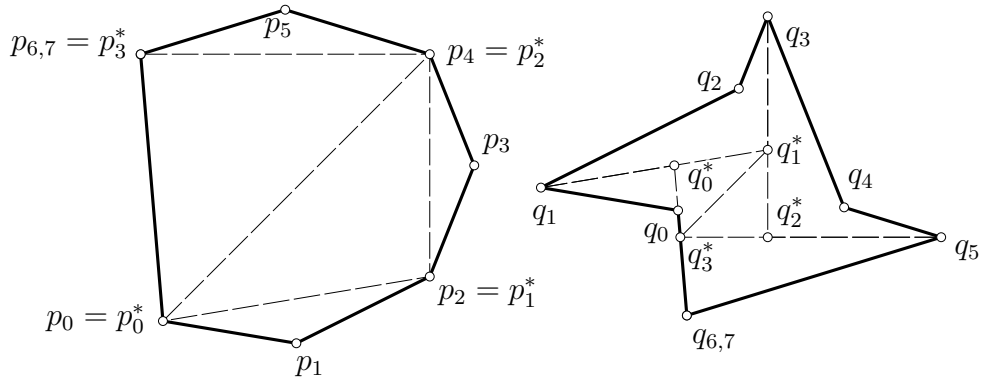


FIGURE 11. Parallel 7-gons P, Q with vanishing mixed area, which are interpreted as 8-gons with $p_6 = p_7$ and $q_6 = q_7$, respectively. The derived polygons P^*, Q^* are parallel quads with $\text{area}(P^*, Q^*) = 0$ and consequently antiparallel diagonals.

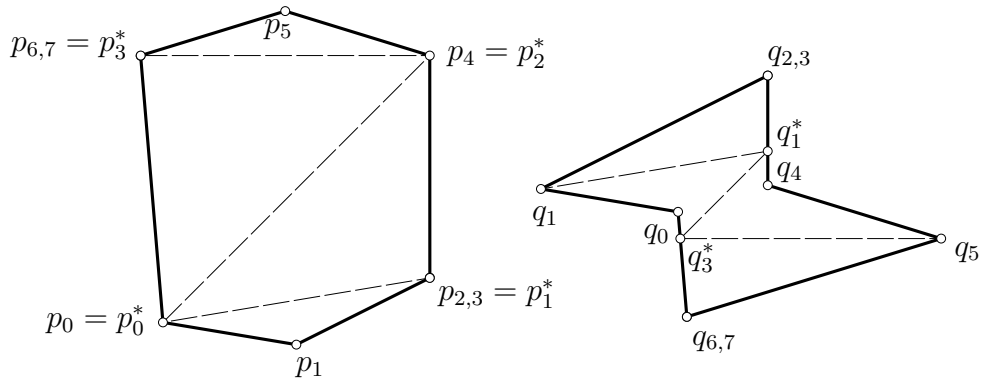


FIGURE 12. Parallel hexagons P, Q with vanishing mixed area, which are interpreted as 8-gons with $p_6 = p_7, p_2 = p_3$ and $q_6 = q_7, q_2 = q_3$ respectively. The derived polygons P^*, Q^* are parallel quads with $\text{area}(P^*, Q^*) = 0$ and consequently antiparallel diagonals. For a geometric characterization, only one half of Q^* is needed.

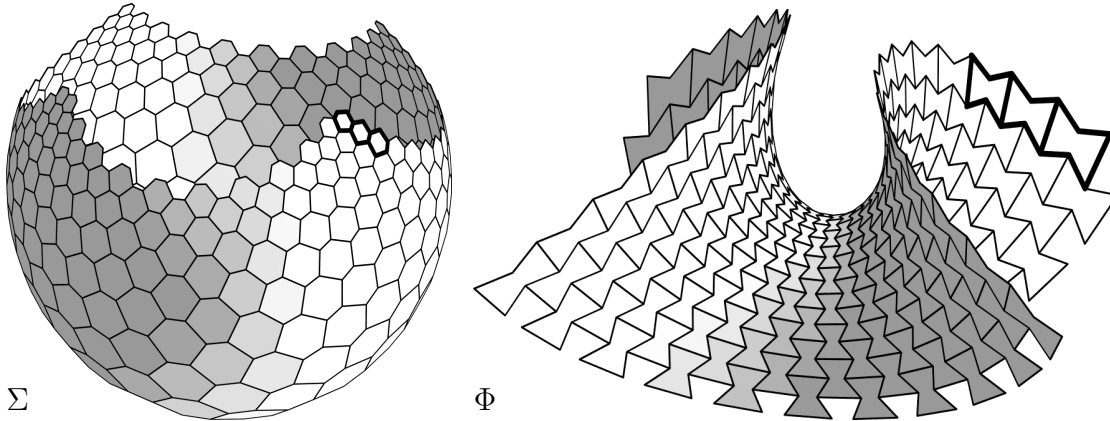


FIGURE 13. A discrete Enneper's surface Φ in the shape of a hexagonal mesh, which corresponds to a spherical mesh Σ by a discrete Christoffel duality. The marked hexagons correspond to each other.

Not every quadrilateral mesh Σ with planar faces (i.e., a polyhedral surface with regular grid combinatorics) has a Christoffel dual Φ : It turns out that exactly the Koenigs nets (see [3, 4]) have this property.

4.1. Construction of hexagonal minimal surfaces. Figure 13 illustrates a parallel pair (Σ, Φ) of meshes (for more details, see the example below). The faces of Σ are tangent to the unit sphere, so it makes sense to consider Σ as a discrete Gauss image of Φ . As Φ has been constructed such that the mixed area of corresponding faces vanishes, Φ is discrete minimal. It should be mentioned in this place that the exact relation between the discrete Gauss image Σ and the unit sphere S^2 can be of a different nature: We could also require that vertices of Σ lie in S^2 , or its edges are tangent to S^2 . The three cases of vertices, edges, and faces having an exact tangency relation with S^2 correspond to the mesh Φ having offset meshes $\Phi + d\Sigma$ at constant vertex-vertex distance d , or edge-edge distance d , or face-face distance d [7, 6]. Note that the property of vanishing mixed area does not only occur between minimal surface and Gauss image, but also between a surface Φ of constant mean curvature H with respect to a Gauss image Σ , and its offset $\Phi + \frac{1}{H}\Sigma$.

The construction of a discrete Christoffel dual (i.e., Φ from Σ) for hexagonal meshes is easy, as there are enough degrees of freedom. The fact that $\dim \mathcal{P}(P) = 4$ leads to a three-dimensional space of parallel polygons Q with $\text{area}(P, Q) = 0$. Consequently adding a new hexagon of Φ to already constructed ones is an operation which has $3 - k$ degrees of freedom, where k is the number of known vertices (which are shared with already existing neighbours of the hexagon to be constructed).

Example. Figure 13 shows a hexagonal mesh Σ which is circumscribed to the unit sphere and its Christoffel dual mesh Φ which assumes the shape of an Enneper's

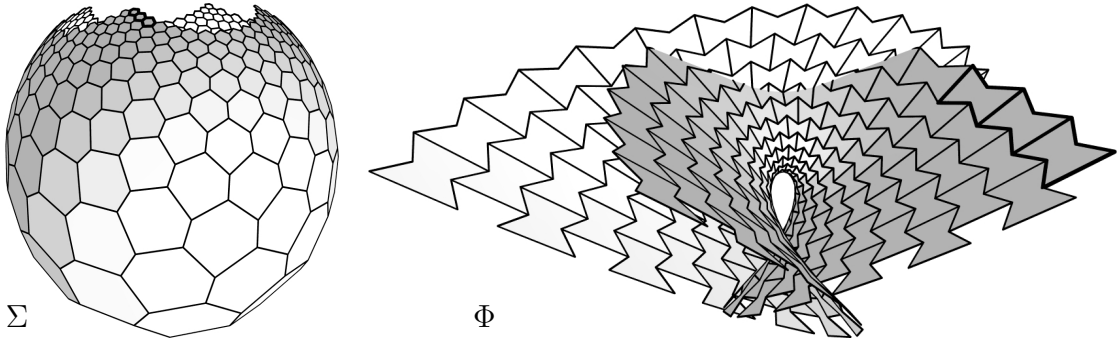


FIGURE 14. A discrete Enneper's surface created in the same way as Figure 13, but with a different size of the spherical mesh Σ . Here Φ has self-intersections. The viewpoint is different from that of Figure 13.

surface. This example is constructed as follows: We start with an isothermic curvature-line parametrization $x(u, v)$ of the known smooth Enneper's surface M . Next we tile the parameter domain with non-convex hexagons — we used dilates of the hexagon with vertices $(0, 0)$, $(\frac{1}{2}, \frac{1}{4})$, $(1, 0)$, $(1, 1)$, $(\frac{1}{2}, \frac{3}{4})$, $(0, 1)$. Mapping the vertices of this tiling with the parametrization x yields a hexagonal mesh Φ_0 with non-planar faces inscribed to M (it looks very much like Figure 13, right). Each planar hexagon has a center, say (u^*, v^*) , and we consider $x(u^*, v^*)$ as the center of the corresponding spatial hexagon. Next we construct the mesh Σ by parallel translating the tangent planes of M in the centers of hexagons such that they touch the unit sphere. Vertices of Σ are found by intersection of planes (see Figure 13, left). Having constructed Σ , we find its Christoffel dual Φ by optimizing Φ_0 such that mixed areas of corresponding faces in Σ and Φ are zero, and such that corresponding edges are parallel. This amounts to minimizing a quadratic function, here done by a standard conjugate gradient method, which turns out not change the shape of Φ_0 much despite the fact that the theoretical number of degrees of freedom is larger.

4.2. Reciprocal parallelity in discrete minimal surfaces. In the quad mesh case, there is an interesting connection of minimal surfaces with *reciprocal-parallel meshes*. A reciprocal-dual mesh pair is defined as meshes which are combinatorial duals of each other (there is a correspondence face–vertex, vertex–face, and edge–edge), such that corresponding edges are parallel [8]. Proposition 2 immediately shows that Φ is a minimal surface with respect to Σ if meshes composed from diagonals of quads in both Σ, Φ are reciprocally parallel [6]. This is illustrated in Figure 15. It should be mentioned that reciprocal parallelity of meshes in connection with discrete minimal surfaces also occurs in other places, for instance in [10].

For *hexagonal* meshes, we similarly can derive pairs of reciprocal-parallel meshes from a Christoffel dual pair (Σ, Φ) . The geometric characterization of vanishing

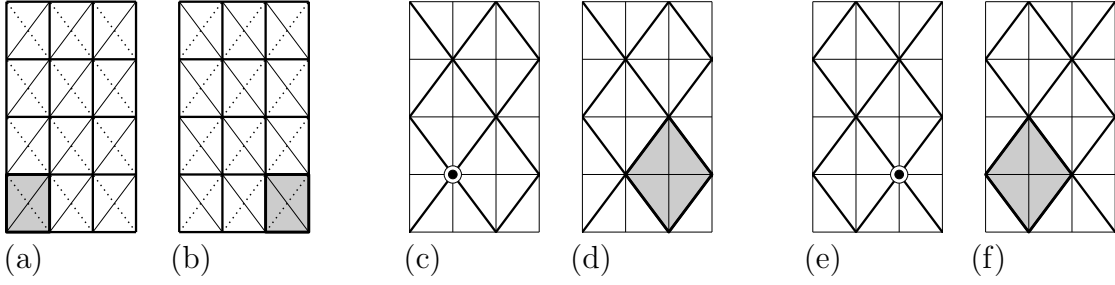


FIGURE 15. Reciprocal-parallel meshes derived from a quadrilateral mesh Σ and its Christoffel dual mesh Φ , which is combinatorially equivalent such that corresponding quadrilaterals P and Q have vanishing mixed area. From left: (a) Mesh Σ with face P . (b) Mesh Φ with face Q corresponding to P . (c) Quadrilateral mesh Σ' composed from one half of diagonals of Σ . (d) Those diagonals in Φ which are parallel to the previous ones according to Proposition 2 constitute a mesh Φ' reciprocal-parallel to Σ' : vertices in Σ' correspondence faces of Φ' . (e) and (f) show the reciprocal-parallel mesh pair Σ'' , Φ'' composed from the diagonals omitted in (c) and (d).

mixed area according to Theorem 7 and Figure 7 leads to the configuration of lines in meshes Σ and Φ , which is illustrated in Figures 16a and 16b. Obviously, the configuration of diagonals in Σ (Figure 16c) is reciprocally parallel to the configuration of lines in Φ , which consist of the to-be edges of degenerate derived polygons (Figure 16d). A different choice of diagonals in Σ would lead to a different pair of reciprocal-parallel meshes.

Obviously for each vertex of Σ^* , the cycle of edge vectors adjacent to the corresponding face of Φ^* serves as equilibrium forces acting on that vertex. Thus, Φ^* represents a collection of equilibrium forces for Σ^* . These forces (scaled) are shown by Figure 16c.

As the relation $\text{area}(P, Q) = 0$ is symmetric, the geometric configuration of the triangle P^* and the degenerate triangle Q^* exists also if the roles of P and Q (i.e., the roles of Σ and Φ) are exchanged: One half of the diagonals in Φ constitute a triangle mesh Φ^{**} , which possesses a reciprocal-parallel hexagonal mesh Σ^{**} associated with Σ (see Figures 16e and 16f). Figure 16f also shows equilibrium forces for Φ^{**} which are a scaled version of the edges of Σ^{**} .

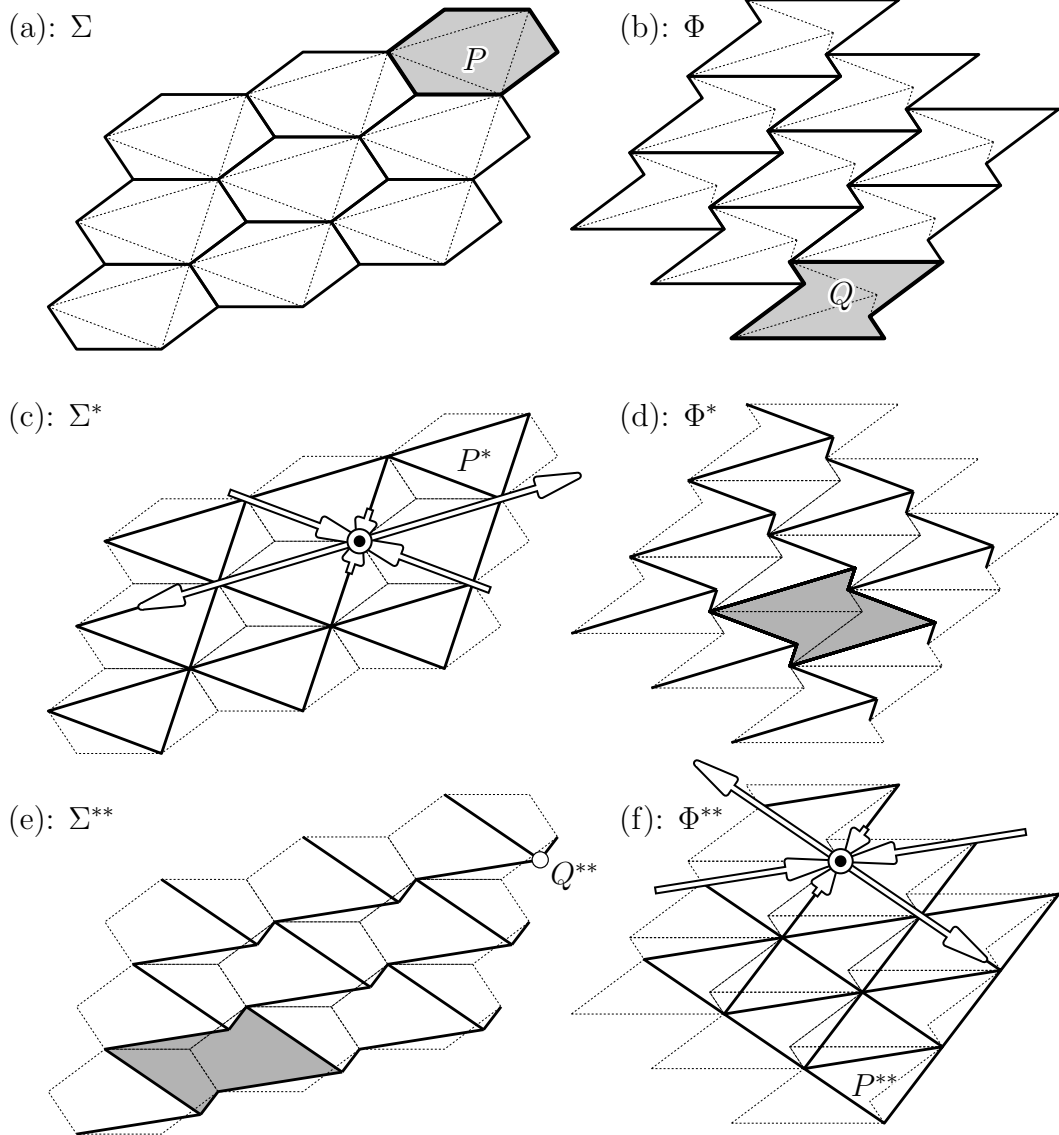


FIGURE 16. Reciprocal-parallel meshes Σ', Φ' in bottom row derived from Christoffel-dual meshes Σ, Φ in top row. The edges around a face in Φ' serve as equilibrium forces acting in the edges adjacent to the corresponding vertex of Σ' . (a) Hexagonal mesh Σ with face P . (b) Hexagonal mesh Φ of the same combinatorics such that corresponding faces P of Σ and Q of Φ have vanishing mixed area. (c) Triangle mesh whose edges are derived polygons P^* in mesh Σ . (d) Hexagonal mesh whose edges are the lines q_1q^* , q_3q^* , q_5q^* in each hexagon of Φ , where q^* is the degenerate polygon Q^* . Note that Φ^* does not have planar faces. In (e) and (f), the geometric characterization of vanishing mixed area which yields diagonals and their parallels is read in reverse order compared to (a)–(d): Diagonals are taken from the non-convex hexagons in the mesh Φ .

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AUTHORS' ADDRESS: INSTITUTE OF GEOMETRY, TU GRAZ. KOPERNIKUSGASSE 24, 8010 GRAZ, AUSTRIA. EMAIL: {CHRISTIAN.MUELLER, J.WALLNER}@TUGRAZ.AT