Discrete Torsion of Connection Forms on Simplicial Meshes
Supplemental Material

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This supplemental material contains pseudocode for our algorithm in Section 1, and provides additional details on the derivation of our analytical reference solution for the convergence test of the discrete Levi-Civita connection in Section 2.

1 Pseudocode

Our pseudocode is expressed via a halfedge mesh data structure encoding a triangle mesh $M = (\mathcal{V}, \mathcal{E}, \mathcal{F})$. We use $\overrightarrow{ij} \in \mathcal{H}$ to denote the halfedge from i to j, and use $\mathring{\mathcal{H}}$ to denote the set of halfedges which run along interior edges (*i.e.*, the set of edges on which our trivial connection stores meaningful values). We make use of standard halfedge operations such as $\textsc{Halfedge}(f)$ which returns the first halfedge in face f according to the mesh data structure's ordering.

We write vectors $(a, b) \in \mathbb{R}^2$ as complex numbers $z = a + b\mathbf{i} \in \mathbb{C}$, and use the argument $\textsc{Arg}(a + b\mathbf{i}) := \operatorname{atan2}(b, a)$, the scalar cross product $(a + b\mathbf{i}) \times (c + d\mathbf{i}) := ad - bc$, and the complex inverse $(a + b\mathbf{i})^{-1} := (a - b\mathbf{i})/(a^2 + b^2)$. We also write our face frames as complex numbers. On each face f, we let F_x be the unit vector pointing along $\textsc{Halfedge}(f)$, and let F_y be the unit vector rotated 90° counter-clockwise in the plane of f. Then $E_f = a + b\mathbf{i}$ denotes a frame with x-axis $e_x = aF_x + bF_y$ and y-axis $e_y = -bF_x + aF_y$.

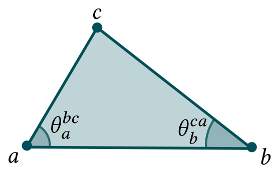
We also use the following standard quantities and subroutines:

- θ_i^{jk} is the corner angle of triangle ijk at vertex i.
- $d_1 \in \mathbb{Z}^{\mathcal{F}\times\mathcal{E}}$ is the discrete exterior derivative on 1-forms, *i.e.* the face-edge signed incidence matrix.
- $\textsc{AngleSums}(M, \ell)$ returns a vector $\Phi \in \mathbb{R}^{\mathcal{V}}$ containing the sum of corner angles around each vertex i.
- $\textsc{AngleDefects}(M, \ell)$ returns a vector $K \in \mathbb{R}^{\mathcal{V}}$ containing the angle defect around each vertex i (Explicitly, K_i is $2\pi - \Phi_i$ for interior vertices, and $\pi - \Phi_i$ for boundary vertices).
- $\textsc{LayOutDiamond}(M, \ell, \overrightarrow{ij})$ returns positions $p_i, p_j, p_k, p_l \in \mathbb{C}$ for the vertices of the two adjacent triangles ijk, jil (see *e.g.* Sharp et al. [2021, Appendix A]).

Algorithm 1 $\textsc{HalfedgeDirectionInFaceFrame}(M, \ell, E, \overrightarrow{ij})$

Input: A moving frame $E \in \mathbb{C}^{\mathcal{F}}$ and halfedge $\overrightarrow{ij}$ on a mesh M with edge lengths ℓ.
Output: The vector $z \in \mathbb{C}$ indicating the direction in which $\overrightarrow{ij}$ points when written in frame E.

```
1: $abc \leftarrow \textsc{Face}(\overrightarrow{ij})$
2: if $\overrightarrow{ij} == \overrightarrow{ab}$ then
3:     return $E_f^{-1}$
4: else if $\overrightarrow{ij} == \overrightarrow{bc}$ then
5:     return $-\exp\left(-\mathbf{i}\,\theta_b^{ca}\right) E_f^{-1}$
6: else  # $\overrightarrow{ij} == \overrightarrow{ca}$
7:     return $-\exp\left(\mathbf{i}\,\theta_a^{bc}\right) E_f^{-1}$
```



Algorithm 2 $\textsc{ComputeHingeConnection}(M, \ell, E)$

Input: A moving frame $E \in \mathbb{C}^{\mathcal{F}}$ on a mesh M with edge lengths ℓ.
Output: The hinge connection $\eta \in \mathbb{R}^{\mathcal{H}}$, written in frame E.

```
1: for each $\overrightarrow{ij} \in \mathring{\mathcal{H}}$ do
2:     $z_{\overrightarrow{ij}} \leftarrow \textsc{HalfedgeDirectionInFaceFrame}(M, \ell, E, \overrightarrow{ij})$
3:     $z_{\overrightarrow{ji}} \leftarrow \textsc{HalfedgeDirectionInFaceFrame}(M, \ell, E, \overrightarrow{ji})$
4:     $\eta_{\overrightarrow{ij}} \leftarrow \textsc{Arg}(-z_{\overrightarrow{ij}}/z_{\overrightarrow{ji}})$
5: return $\eta$
```

Algorithm 3 $\textsc{ComputeDiscreteLeviCivitaOffset}(M, \ell, b)$

Input: A mesh M with edge lengths ℓ, and a matrix $b \in \mathbb{R}^{3\times\mathcal{F}}$ giving the location of the dual vertex of each face ijk written in barycentric coordinates on ijk. We use b_i^{jk} to denote the barycentric coordinate associated to vertex i within face ijk.
Output: A discrete 1-form $\lambda \in \mathbb{R}^{\mathcal{E}}$ giving the difference between the discrete Levi-Civita connection and the hinge connection.

```
1: $\Phi, K \leftarrow \textsc{AngleSums}(M, \ell), \textsc{AngleDefects}(M, \ell)$
2: $A \leftarrow 0 \in \mathbb{R}^{\mathcal{V}}$    # zero-initialize dual areas
3: for each $\overrightarrow{ij} \in \mathring{\mathcal{H}}$ do
4:     $p_i, p_j, p_k, p_l \leftarrow \textsc{LayOutDiamond}(M, \ell, \overrightarrow{ij})$
5:     $p_{ijk} \leftarrow b_i^{jk} p_i + b_j^{ki} p_j + b_k^{ij} p_k$    # location in planar layout
6:     $p_{jil} \leftarrow b_j^{il} p_j + b_i^{lj} p_i + b_l^{ji} p_l$
7:     $\varphi_{*ij} \leftarrow \textsc{Arg}\left[(p_{jil} - p_i)/(p_{ijk} - p_i)\right]$    # dual corner angle
8:     $A_{*ij} \leftarrow \frac{1}{2}(p_{jil} - p_i) \times (p_{ijk} - p_i)$    # dual triangle area
9:     $A_i \leftarrow A_i + A_{*ij}$    # add triangle area to vertex dual area
10: for each $ij \in \mathcal{E}$ do    # Equation 8 of the main paper
11:     $\lambda_{ij} \leftarrow \frac{1}{A_{*ij}+A_{*ji}} \left( K_i A_{*ij} \left( \frac{A_{*ij}}{A_i} - \frac{\varphi_{*ij}}{\Phi_i} \right) - K_j A_{*ji} \left( \frac{A_{*ji}}{A_j} - \frac{\varphi_{*ji}}{\Phi_j} \right) \right)$
12: return $\lambda$
```

Algorithm 4 $\textsc{ComputeTorsionConnectionOffset}(M, \ell, b, p)$

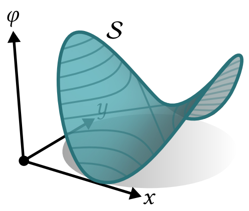
Input: A mesh $M = (\mathcal{V}, \mathcal{E}, \mathcal{F})$ with given edge lengths ℓ, a matrix $b \in \mathbb{R}^{3\times\mathcal{F}}$ giving the locations of the dual vertices, and a scalar torsion potential $p \in \mathbb{R}^{\mathcal{F}}$.
Output: A discrete 1-form $\mu \in \mathbb{R}^{\mathcal{E}}$ giving the difference between the discrete Levi-Civita connection and the connection with the desired torsion dp.

```
1: return $\textsc{ComputeDiscreteLeviCivitaOffset}(M, \ell, b) + d_1^T p$
```

Note. When using the simple construction of the hinge map η in Algorithm 2, the differential $(d\eta)_i$ at a vertex i may differ from the angle defect K_i by a multiple of 2π. When running trivial connections, one should use K_i as the initial connection curvature to ensure that Gauss-Bonnet is satisfied. Similarly, when starting from another connection $\alpha = \eta + \lambda$, using $K + d\lambda$ as the initial connection curvature ensures that Gauss-Bonnet is satisfied.

2 Connections on Quadratic Surfaces

Let $A \in \mathbb{R}^{2\times 2}$ be a symmetric matrix. Then A gives rise to a quadratic form $\varphi : \mathbb{R}^2 \to \mathbb{R}$, where $\varphi : p \mapsto \frac{1}{2}p^T Ap$, which defines a surface



$$\mathcal{S} = \left\{\left(x, y, \varphi(x,y)\right)\right\} \subset \mathbb{R}^3. \quad (1)$$

The surface $\mathcal{S}$ has a natural parameterization $f(p) = (p, \varphi(p))$.

Metric. The metric of $\mathcal{S}$ at a point $p \in \mathbb{R}^2$ in our parameterization is $g_p = df_p^T df_p$. The differential of f is

$$df_p = \begin{pmatrix} \mathbb{I} \\ (Ap)^T \end{pmatrix}, \quad (2)$$

so the metric is given explicitly by

$$g_p = df_p^T df_p = \mathbb{I} + (Ap)\,(Ap)^T\,. \quad (3)$$

Normals. We can write $\mathcal{S}$ as a level set of $\psi(x,y,z) = \varphi(x,y) - z$, so the normal of $\mathcal{S}$ points along $\nabla\psi$. The unit normal is thus

$$\hat{n}_p = \frac{1}{\sqrt{1 + p^T A^2 p}} \begin{pmatrix} Ap \\ -1 \end{pmatrix}. \quad (4)$$

Covariant Derivative. To compute the covariant derivative operator, we start with a vector field $V(p)$ in the plane and define a lifted field tangent to the surface $\mathcal{S}$:

$$f_* V = \begin{pmatrix} V(p) \\ \varphi_* V(p) \end{pmatrix} = \begin{pmatrix} V(p) \\ p^T AV(p) \end{pmatrix} \quad (5)$$

In order to evaluate the covariant derivative $\nabla^{\mathcal{S}}_W V$ in direction $W \in \mathbb{R}^2$, we start by evaluating the $\mathbb{R}^3$ directional derivative

$$\nabla^{\mathbb{R}^2}_W (f_* V) = \begin{pmatrix} \nabla^{\mathbb{R}^2}_W V \\ p^T A \nabla^{\mathbb{R}^2}_W V + W^T AV \end{pmatrix}. \quad (6)$$

The covariant derivative projects out the normal component of this directional derivative:

$$\nabla^{\mathbb{R}^2}_W f_* V - n_p n_p^T \nabla^{\mathbb{R}^2}_W f_* V = \nabla^{\mathbb{R}^2}_W f_* V + \begin{pmatrix} Ap \\ -1 \end{pmatrix} \frac{W^T AV}{1 + p^T A^2 p}. \quad (7)$$

Pulling this $\mathbb{R}^3$-valued expression back to the xy-plane by taking the first two components yields the intrinsic expression:

$$\nabla^{\mathcal{S}}_W V = \nabla^{\mathbb{R}^2}_W V + \frac{W^T AV}{1 + p^T A^2 p} Ap. \quad (8)$$

(The third component of Equation 7 is the lift $\varphi_* \nabla^{\mathcal{S}}_W V = p^T A \nabla^{\mathcal{S}}_W V$.)

Parallel Transport. Now, consider the radial curve $\gamma(t) = tq$ to a vector $q \in \mathbb{R}^2$. In general γ is not geodesic, but we can still parallel transport vectors V along γ using the parallel transport equation

$$\nabla^{\mathcal{S}}_{\dot{\gamma}} V = 0. \quad (9)$$

If we consider $V(t)$ as a function of time along γ and expand out the covariant derivative expression from Equation 8, we obtain

$$\dot{V} = -\frac{\dot{\gamma}^T AV}{1 + \gamma^T A^2 \gamma} A\gamma = -\frac{t}{1 + t^2 q^T A^2 q} \left[(Aq)\,(Aq)^T\right] V. \quad (10)$$

When $V(0)$ is orthogonal to Aq (with respect to the standard inner product on $\mathbb{R}^2$), then the parallel field $V(t) = V(0)$ is constant. When $V(0)$ points along Aq, then $V(t)$ always points in the same direction—making the ansatz $V(t) = \lambda(t)Aq$, yields the equation

$$\dot{\lambda}(t)Aq = -\frac{tq^T A^2 q}{1 + t^2 q^T A^2 q} \lambda(t)Aq, \quad (11)$$

One can check that the solution $\lambda(t)$ with $\lambda(0) = 1$ is given by

$$\lambda(t) = \frac{1}{\sqrt{1 + t^2 q^T A^2 q}}. \quad (12)$$

Finally, we convert back to the standard basis of $\mathbb{R}^2$:

$$V(t) = \begin{pmatrix} Aq & \mathbb{J}Aq \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{1+t^2 q^T A^2 q}} & 0 \\ 0 & 1 \end{pmatrix} \frac{\begin{pmatrix} Aq & \mathbb{J}Aq \end{pmatrix}^T}{q^T A^2 q} V_0 \quad (13)$$

$$= \left(\frac{1}{\sqrt{1+t^2 q^T A^2 q}} \frac{(Aq)\,(Aq)^T}{q^T A^2 q} + \frac{(\mathbb{J}Aq)\,(\mathbb{J}Aq)^T}{q^T A^2 q} \right) V_0, \quad (14)$$

where we have used the fact that $\begin{pmatrix} Aq & \mathbb{J}Aq \end{pmatrix}$ is an orthogonal matrix, so its inverse is its transpose divided by $\|Aq\|^2_{\mathbb{R}^2}$.

Parallel-Propagated Frame. We compute a parallel-propagated frame and its dual coframe by parallel transporting the standard basis at the origin along radial lines, yielding

$$E_p = V(1) = \frac{1}{\sqrt{1+p^T A^2 p}} \frac{(Ap)\,(Ap)^T}{p^T A^2 p} + \frac{(\mathbb{J}Ap)\,(\mathbb{J}Ap)^T}{p^T A^2 p}, \quad (15)$$

$$\theta_p = E_p^T g_p = \sqrt{1 + p^T A^2 p}\, \frac{(Ap)\,(Ap)^T}{p^T A^2 p} + \frac{(\mathbb{J}Ap)\,(\mathbb{J}Ap)^T}{p^T A^2 p}. \quad (16)$$

Levi-Civita-Connection. To find the Levi-Civita connection, we write θ_p in Cartesian coordinates with components $\lambda_0, \lambda_1, \mu_0, \mu_1$:

$$\theta_p = \begin{pmatrix} \lambda_0 dx + \mu_0 dy \\ \lambda_1 dx + \mu_1 dy \end{pmatrix}, \quad (17)$$

In the parallel-propagated frame, the Levi-Civita connection is $\omega = \mathbb{J}\alpha = \mathbb{J}\,(\alpha_0 dx + \alpha_1 dy)$. The Cartan structure equations are thus

$$0 = d\theta_p + \omega_p \wedge \theta_p \quad (18)$$

$$= \left(\begin{pmatrix} \frac{\partial \mu_0}{\partial x} - \frac{\partial \lambda_0}{\partial y} \\ \frac{\partial \mu_1}{\partial x} - \frac{\partial \lambda_1}{\partial y} \end{pmatrix} + \begin{pmatrix} 0 & -\alpha \\ \alpha & 0 \end{pmatrix} \begin{pmatrix} \lambda_0 dx + \mu_0 dy \\ \lambda_1 dx + \mu_1 dy \end{pmatrix} \right) dx \wedge dy \quad (19)$$

$$= \left(\begin{pmatrix} \frac{\partial \mu_0}{\partial x} - \frac{\partial \lambda_0}{\partial y} \\ \frac{\partial \mu_1}{\partial x} - \frac{\partial \lambda_1}{\partial y} \end{pmatrix} + \begin{pmatrix} -\mu_1 & \lambda_1 \\ \mu_0 & -\lambda_1 \end{pmatrix} \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix} \right) dx \wedge dy \quad (20)$$

One can check that the following α_p solves Equation 20, yielding the desired connection 1-form in the parallel-propagated frame:

$$\alpha_p = \frac{\det(A)}{1 + p^T A^2 p + \sqrt{1 + p^T A^2 p}} (y\,dx - x\,dy). \quad (21)$$

For convenience, we include a Mathematica notebook to compute α_p directly. At the origin, $\det(A)$ is the Gaussian curvature κ, so:

$$\alpha_{\text{origin}} = \tfrac{1}{2}\det(A)(y\,dx - x\,dy) = \tfrac{1}{2}\kappa(y\,dx - x\,dy). \quad (22)$$

Around any point p, we can approximate $\mathcal{S}$ up to second order by a paraboloid centered at p with the same Gaussian curvature as $\mathcal{S}$ at p. Thus, in the parallel-propagated frame at p we have a second order accurate approximation $\alpha_p \approx \frac{1}{2}\kappa_p(y\,dx - x\,dy)$. We use this expression for the convergence tests in Sec. 4.3 of the main paper.

References

Nicholas Sharp, Mark Gillespie, and Keenan Crane. 2021. Geometry Processing with Intrinsic Triangulations. (July 2021). https://doi.org/10.1145/3450508.3464592

This notebook demonstrates the calculation of the Levi-Civita connection of a quadratic surface expressed in cartesian coordinates in the parallel propagated frame based at the origin.

Given a symmetric matrix A, we can define a height field

$c : \mathrm{R}^2 \to \mathrm{R}^3 : p = (x, y) \mapsto \left(x, y, \frac{1}{2} p^t A p\right)$

and a quadratic surface $M = c\left(\mathrm{R}^2\right) \subset \mathrm{R}^3$ as the image

In[573]:=

```
(*Define the matrix that will form the quadratic form*)
A = {{a, d}, {d, b}};
J = {{0, -1}, {1, 0}};
```

In[510]:=

```
(*Define the surface in cartesian coordinates*)
c[x_, y_] := {
    x,
    y,
    ({x, y}.A.{x, y}) / 2
   };
```

In[511]:=

```
DcDx = D[c[x, y], x] // Simplify;
DcDy = D[c[x, y], y] // Simplify;
```

Now, for this frame we calculate the first fundamental form.

In[513]:=

```
g00 = FullSimplify[DcDx.DcDx];
g01 = FullSimplify[DcDx.DcDy];
g11 = FullSimplify[DcDy.DcDy];
```

In[519]:=

```
FirstFundamentalForm = {{g00, g01}, {g01, g11}};
```

Based on the expression in the supplemental material to our paper *"Discrete Torsion of Connection Forms on Simplicial Meshes"* we calculate the parallel propagated frame based in the origin. We parallel propagate the standard frame along radial lines leaving the origin.

In[524]:=

```
q = {x, y};
Aq = A.q;
JAq = J.Aq;
qA2q = q.A.A.q;
```

We showed that given a vector V_0 in the tangent space at the origin, and a direction vector $q \in \mathrm{R}^2$, the parallel transported vector along the curve $\gamma(t) = t\,q$ is given by

$$V(t) = \left(\frac{1}{\sqrt{1 + t^2 q^T A^2 q}} \frac{(A q)(A q)^T}{q^T A^2 q} + \frac{(\mathbf{J} A q)(\mathbf{J} A q)^T}{q^T A^2 q} \right) V_0,$$

In[528]:=
```
PPFMatrix =
  (1 / Sqrt[1 + qA2q]) * (Outer[Times, Aq, Aq] / qA2q) + (Outer[Times, JAq, JAq] / qA2q);
```

Therefore, evaluated at a point $p = (x, y)$, the parallel propagated standard frame is given by

In[529]:=
```
PPFX = PPFMatrix.{1, 0};
PPFY = PPFMatrix.{0, 1};
```

Now, we can do a sanity check to ensure the orthonormality of the PPF with respect to the first fundamental form.

In[588]:=
```
OrthoCheck00 = FullSimplify[PPFX.(FirstFundamentalForm.PPFX)];
OrthoCheck10 = FullSimplify[PPFY.(FirstFundamentalForm.PPFX)];
OrthoCheck11 = FullSimplify[PPFY.(FirstFundamentalForm.PPFY)];
{{OrthoCheck00, OrthoCheck10}, {OrthoCheck10, OrthoCheck11}} // MatrixForm
```

Out[591]//MatrixForm=

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

We can express the PPF in cartesian coordinates via
$e_{1\,\mathrm{PPF}} = \alpha_1\,\partial_x + \beta_1\,\partial_y$ and $e_{2\,\mathrm{PPF}} = \alpha_2\,\partial_x + \beta_2\,\partial_y$
We are now aiming to find the dual Parallel-Propagated frame
e^1_{PPF} and e^2_{PPF}. We will stick to cartesian coordinates, i.e we define scalar functions $\lambda_1, \lambda_2, \mu_1, \mu_2$,
such that $e^1_{\mathrm{PPF}} = \lambda_1\,d\,x + \mu_1\,d\,y$ and $e^2_{\mathrm{PPF}} = \lambda_2\,d\,x + \mu_2\,d\,y$ is the dual frame.

The coefficients for the dual frame are given by

$$\theta = \frac{1}{p^T A^2 p}\left(\sqrt{1 + p^T A^2 p}\;(A\,p)\,(A\,p)^T + (\mathrm{J}\,A\,p)\,(\mathrm{J}\,A\,p)^T\right):$$

In[535]:=
```
{{λ1, μ1}, {λ2, μ2}} =
  Sqrt[1 + qA2q] (Outer[Times, Aq, Aq] / qA2q) + (Outer[Times, JAq, JAq] / qA2q);
```

Now, we can do a sanity check to see ensure that $e^i_{\mathrm{PPF}}\left(e_{j\,\mathrm{PPF}}\right) = \delta_{i\,j}$

In[556]:=
```
check00 = FullSimplify[{λ1, μ1}.PPFX];
check10 = FullSimplify[{λ2, μ2}.PPFX];
check01 = FullSimplify[{λ1, μ1}.PPFY];
check11 = FullSimplify[{λ2, μ2}.PPFY];
{{check00, check10}, {check01, check11}} // MatrixForm
```

Out[560]//MatrixForm=

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Now, we are aiming to solve the Cartan structure equations for the Levi-Civita connection. This means, we are searching for a 1-form $\alpha = \omega_1\,d\,x + \omega_2\,d\,y$ such that

$$d\begin{pmatrix} e^1_{\mathsf{PPF}} \\ e^2_{\mathsf{PPF}} \end{pmatrix} + \begin{pmatrix} 0 & -\alpha \\ \alpha & 0 \end{pmatrix} \wedge \begin{pmatrix} e^1_{\mathsf{PPF}} \\ e^2_{\mathsf{PPF}} \end{pmatrix} = 0$$

Here, d denotes the ordinary exterior derivative on 1-forms. It holds

$$d\begin{pmatrix} e^1_{\mathsf{PPF}} \\ e^2_{\mathsf{PPF}} \end{pmatrix} = \begin{pmatrix} \frac{\partial\mu_1}{\partial x} - \frac{\partial\lambda_1}{\partial y} \\ \frac{\partial\mu_2}{\partial x} - \frac{\partial\lambda_2}{\partial y} \end{pmatrix} d\,x \wedge d\,y$$

In[561]:=
```
DLambda1Dy = FullSimplify[D[λ1, y]];
DLambda2Dy = FullSimplify[D[λ2, y]];
DMu1Dx = FullSimplify[D[μ1, x]];
DMu2Dx = FullSimplify[D[μ2, x]];
```

In[565]:=
```
dPPFX = FullSimplify[DMu1Dx - DLambda1Dy];
dPPFY = FullSimplify[DMu2Dx - DLambda2Dy];
dPPF = {dPPFX, dPPFY};
```

It holds for the wedge product

$$\begin{pmatrix} 0 & -\alpha \\ \alpha & 0 \end{pmatrix} \wedge \begin{pmatrix} e^1_{\mathsf{PPF}} \\ e^2_{\mathsf{PPF}} \end{pmatrix} = \begin{pmatrix} -\alpha \wedge e^1_{\mathsf{PPF}} \\ \alpha \wedge e^2_{\mathsf{PPF}} \end{pmatrix} =$$

$$\begin{pmatrix} -\omega_1\,\mu_2 + \omega_2\,\lambda_2 \\ \omega_1\,\mu_1 - \omega_2\,\lambda_1 \end{pmatrix} d\,x \wedge d\,y = \begin{pmatrix} -\mu_2 & \lambda_2 \\ \mu_1 & -\lambda_1 \end{pmatrix}\begin{pmatrix} \omega_1 \\ \omega_2 \end{pmatrix} d\,x \wedge d\,y$$

In[568]:=
```
BforCartanStructure = FullSimplify[{{-μ2, λ2}, {μ1, -λ1}}];
```

We can therefore now solve for the coefficients of the Levi-Civita connection

In[596]:=
```
{ω1, ω2} = FullSimplify[LinearSolve[BforCartanStructure, -dPPF]]
```

Out[596]=

$$\Big\{\Big(\big(a\,b - d^2\big)\,y\,\Big(1 + \big(a^2 + d^2\big)\,x^2 + 2\,(a+b)\,d\,x\,y + \big(b^2 + d^2\big)\,y^2 - \sqrt{1 + \big(a^2 + d^2\big)\,x^2 + 2\,(a+b)\,d\,x\,y + \big(b^2 + d^2\big)\,y^2}\Big)\Big) \Big/ \Big(\Big(\big(a^2 + d^2\big)\,x^2 + 2\,(a+b)\,d\,x\,y + \big(b^2 + d^2\big)\,y^2\Big)\,\Big(1 + \big(a^2 + d^2\big)\,x^2 + 2\,(a+b)\,d\,x\,y + \big(b^2 + d^2\big)\,y^2\Big)\Big),$$
$$-\Big(\Big(\big(a\,b - d^2\big)\,x\,\Big(1 + \big(a^2 + d^2\big)\,x^2 + 2\,(a+b)\,d\,x\,y + \big(b^2 + d^2\big)\,y^2 - \sqrt{1 + \big(a^2 + d^2\big)\,x^2 + 2\,(a+b)\,d\,x\,y + \big(b^2 + d^2\big)\,y^2}\Big)\Big) \Big/ \Big(\Big(\big(a^2 + d^2\big)\,x^2 + 2\,(a+b)\,d\,x\,y + \big(b^2 + d^2\big)\,y^2\Big)\,\Big(1 + \big(a^2 + d^2\big)\,x^2 + 2\,(a+b)\,d\,x\,y + \big(b^2 + d^2\big)\,y^2\Big)\Big)\Big)\Big\}$$

Finally, we verify the simpler form of the solution given in the supplemental material:

In[576]:=
```
{ω1, ω2} - Det[A] / (1 + qA2q + Sqrt[1 + qA2q]) (-J.q) // FullSimplify
```

Out[576]=
```
{0, 0}
```