Conformal flattening on the probability simplex and its applications to Voronoi partitions and centroids.

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Abstract. A certain class of information geometric structure can be conformally transformed to dually flat one. This paper studys the transformation on the probability simplex from a viewpoint of affine differential geometry [4] and provides its applications. By restricting affine immersions with certain conditions, the probability simplex is realized to be 1-conformally flat [5] statistical manifolds immersed in $\mathbf{R}^{n+1}$. Using this fact, we introduce a concept of conformal flattening of such manifolds to obtain dually flat statistical (Hessian) ones with conformal divergences, and show explicit forms of potential functions, dual coordinates. Finally, we demonstrate applications of the conformal flattening to nonextensive statistical physics, Voronoi partitions and weighted centroids with respect to geometric divergences on the probability simplex.

Keywords: Conformal flattening, Affine differential geometry, Escort probability, Geometric divergence, Computational geometry

1 Introduction

In the theory of information geometry for statistical models, the logarithmic function is crucially significant to give a standard information geometric structure for exponential family [2]. By changing the logarithmic function to the other ones we can deform the standard structure to new one keeping its basic property as a statistical manifold, which consists of a pair of mutually dual affine connections (∇, ∇^*) with respect to Riemannian metric g. There exists several ways $[8, 6, 7]$ to introduce such freedom of functions to deform statistical manifold structure and the functions are sometimes called *embedding* or *representing functions.*

Affine immersion [4] is regarded as one of possible ways. Information geometric structure or *1-conformally flat* statistical manifolds (See Appendix) realized by a certain class of affine immersions can be conformally transformed to dually flat ones [5], which is the most fruitful information geometric structure.

In this paper we call the transformation as *conformal flattening* and give its explicit formula in order to elucidate the relations between representing functions and realized information geometric structures. We also discuss its applicability to computational geometric topics. These are interpreted as generalizations of the results in [10, 11], where the arguments are limited to conformally flattening of the alpha-geometry [1, 2] (See also section 2.4).

The paper is organized as follows: In section 2 we first discuss the affine immersion of the probability simplex and realized geometric structure with the associated *geometric divergences*. Next, conformally flattening transformation is given and the obtained dually flat structure with the associated *conformal divergences* are investigated. Section 3 describes applications of the conformal flattening. We consider a Voronoi partition and a weighted centroid with respect to the geometric divergence on the probability simplex. While geometric divergences are not of Bregman type in general, geometric properties such as conformality and projectivity are well utilized in these topics. We also see that escort probabilities which are interpreted as the dual coordinates play important roles. Section 4 includes a concluding remarks. Finally, a short review on statistical manifolds and affine differential geometry are given in Appendix.

2 Affine immersion of the probability simplex

Let $\mathcal{S}^n$ be the probability simplex defined by

$$\mathcal{S}^n := \left\{ p = (p_i) \,\middle|\, p_i \in \mathbf{R}_+,\ \sum_{i=1}^{n+1} p_i = 1 \right\},$$

where $\mathbf{R}_+$ denotes the set of positive numbers.

Consider an affine immersion [4] (f, ξ) of the simplex $\mathcal{S}^n$ (See also Appendix). Let D be the canonical flat affine connection on $\mathbf{R}^{n+1}$. Further, let f be an immersion from $\mathcal{S}^n$ into $\mathbf{R}^{n+1}$ and ξ be a transversal vector field on $\mathcal{S}^n$. For a given *affine immersion* (f, ξ) of $\mathcal{S}^n$, the induced torsion-free connection ∇ and the affine fundamental form h are defined from the Gauss formula by

$$D_X f_*(Y) = f_*(\nabla_X Y) + h(X, Y)\xi, \quad X, Y \in \mathcal{X}(\mathcal{S}^n), \tag{1}$$

where $\mathcal{X}(\mathcal{S}^n)$ is the set of vector fields on $\mathcal{S}^n$.

It is well known [5, 4] that the realized geometric structure $(\mathcal{S}^n, \nabla, h)$ is a statistical manifold if and only if (f, ξ) is non-degenerate and equiaffine, i.e., h is non-degenerate and $D_X\xi$ is tangent to $\mathcal{S}^n$ for an arbitrary $X \in \mathcal{X}(\mathcal{S}^n)$. Further, a statistical manifold $(\mathcal{S}^n, \nabla, h)$ is 1-conformally flat [5] (, but not necessarily dually flat nor of constant curvature).

Now we consider the affine immersion with the following assumptions.

Assumptions:

1. The affine immersion (f, ξ) is nondegenerate and equiaffine,
2. The immersion f is given by the component-by-component and common representing function L, i.e.,

$$f : \mathcal{S}^n \ni p = (p_i) \mapsto x = (x^i) \in \mathbf{R}^{n+1}, \quad x^i = L(p_i),\ i = 1, \cdots, n+1,$$

3. The representing function $L : (0,\ 1) \to \mathbf{R}$ is sign-definite, concave with $L'' < 0$ and strictly increasing, i.e., $L' > 0$, Hence, the inverse of L denoted by E exists, i.e., $E \circ L = \mathrm{id}$.
4. Each component of ξ satisfies $\xi^i < 0,\ i = 1, \cdots, n+1$ on $\mathcal{S}^n$.

Remark 1. From the assumption 3, it follows that $L'E' = 1$, $E' > 0$ and $E'' > 0$. Regarding sign-definiteness of L, note that we can adjust $L(u)$ to $L(u) + c$ by a suitable constant c without loss of generality since the resultant geometric structure is unchanged (See Proposition 1) by the adjustment. For a fixed L satisfying the assumption 3, we can choose ξ that meets the assumptions 1 and 4. For example, if we take $\xi^i = -|L(p_i)|$ then (f, ξ) is called *centro-affine*, which is known to be equiaffine [4]. The assumptions 3 and 4 also assure positive definiteness of g (The details are described in the proof of Proposition 1). Hence, (f, ξ) is non-degenerate and we can regard g as a Riemannian metric on $\mathcal{S}^n$.

2.1 Conormal vector and the geometric divergence

Define a function Ψ on $\mathbf{R}^{n+1}$ by

$$\Psi(x) := \sum_{i=1}^{n+1} E(x^i),$$

then $f(\mathcal{S}^n)$ immersed in $\mathbf{R}^{n+1}$ is expressed as a level surface of $\Psi(x) = 1$. Denote by $\mathbf{R}_{n+1}$ the dual space of $\mathbf{R}^{n+1}$ and by $\langle \nu, x \rangle$ the pairing of $x \in \mathbf{R}^{n+1}$ and $\nu \in \mathbf{R}_{n+1}$. The conormal vector [4] $\nu : \mathcal{S}^n \to \mathbf{R}_{n+1}$ for the affine immersion (f, ξ) is defined by

$$\langle \nu(p), f_*(X) \rangle = 0,\ \forall X \in T_p\mathcal{S}^n, \qquad \langle \nu(p), \xi(p) \rangle = 1 \tag{2}$$

for $p \in \mathcal{S}^n$. Using the assumptions and noting the relations:

$$\frac{\partial \Psi}{\partial x^i} = E'(x^i) = \frac{1}{L'(p_i)} > 0, \quad i = 1, \cdots, n+1,$$

we have

$$\nu_i(p) := \frac{1}{\Lambda}\frac{\partial \Psi}{\partial x^i} = \frac{1}{\Lambda(p)}E'(x^i) = \frac{1}{\Lambda(p)}\frac{1}{L'(p_i)}, \quad i = 1, \cdots, n+1, \tag{3}$$

where Λ is a normalizing factor defined by

$$\Lambda(p) := \sum_{i=1}^{n+1} \frac{\partial \Psi}{\partial x^i}\xi^i = \sum_{i=1}^{n+1} \frac{1}{L'(p_i)}\xi^i(p). \tag{4}$$

Then we can confirm (2) using the relation $\sum_{i=1}^{n+1} X^i = 0$ for $X = (X^i) \in \mathcal{X}(\mathcal{S}^n)$. Note that $v : \mathcal{S}^n \to \mathbf{R}_{n+1}$ defined by

$$v_i(p) = \Lambda(p)\nu_i(p) = \frac{1}{L'(p_i)}, \quad i = 1, \cdots, n+1,$$

also satisfies

$$\langle v(p), f_*(X)\rangle = 0, \ \forall X \in T_p\mathcal{S}^n. \tag{5}$$

Further, it follows, from (3), (4) and the assumption 4, that

$$\varLambda(p) < 0, \quad \nu_i(p) < 0, \quad i = 1, \cdots, n+1,$$

for all $p \in \mathcal{S}^n$.

It is known [4] that the affine fundamental form h can be represented by

$$h(X,Y) = -\langle \nu_*(X), f_*(Y)\rangle, \quad X, Y \in T_p\mathcal{S}^n.$$

In our case, it is calculated via (5) as

$$\begin{aligned} h(X,Y) &= -\varLambda^{-1}\langle v_*(X), f_*(Y)\rangle - X(\varLambda^{-1})\langle v, f_*(Y)\rangle \\ &= -\frac{1}{\varLambda}\sum_{i=1}^{n+1}\left(\frac{1}{L'(p_i)}\right)' L'(p_i)X^iY^i = \frac{1}{\varLambda}\sum_{i=1}^{n+1}\frac{L''(p_i)}{L'(p_i)}X^iY^i. \end{aligned}$$

Since h is positive definite from the assumptions 3 and 4, we can regard it as a Riemannian metric.

Utilizing these notions from affine differential geometry, we can introduce the function ρ on $\mathcal{S}^n \times \mathcal{S}^n$, which is called a *geometric divergence* [5], as follows:

$$\begin{aligned} \rho(p,r) &= \langle \nu(r), f(p) - f(r)\rangle = \sum_{i=1}^{n+1}\nu_i(r)(L(p_i) - L(r_i)) \\ &= \frac{1}{\varLambda(r)}\sum_{i=1}^{n+1}\frac{L(p_i) - L(r_i)}{L'(r_i)}, \qquad p, r \in \mathcal{S}^n. \end{aligned} \tag{6}$$

We can easily see that ρ is a contrast function [9, 2] of the geometric structure $(\mathcal{S}^n, \nabla, h)$ because it holds that

$$\rho[X|] = 0, \quad h(X,Y) = -\rho[X|Y], \tag{7}$$

$$h(\nabla_X Y, Z) = -\rho[XY|Z], \quad h(Y, \nabla^*_X Z) = -\rho[Y|XZ], \tag{8}$$

where $\rho[X_1 \cdots X_k|Y_1 \cdots Y_l]$ stands for

$$\rho[X_1 \cdots X_k|Y_1 \cdots Y_l](p) := (X_1)_p \cdots (X_k)_p (Y_1)_r \cdots (Y_l)_r \rho(p,r)|_{p=r}$$

for $p, r \in \mathcal{S}^n$ and $X_i, Y_j \in \mathcal{X}(\mathcal{S}^n)$.

2.2 Conformal divergence and 1-conformal transformation

Let σ be a positive function on $\mathcal{S}^n$. Associated with the geometric divergence ρ, the *conformal divergence* [5] of ρ with respect to a conformal factor $\sigma(r)$ is defined by

$$\tilde{\rho}(p,r) = \sigma(r)\rho(p,r), \qquad p, r \in \mathcal{S}^n. \tag{9}$$

The divergence $\tilde{\rho}$ can be proved to be a contrast function for $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$, which is 1-conformally transformed geometric structure from $(\mathcal{S}^n, \nabla, h)$, where $\tilde{h}$ and $\tilde{\nabla}$ are given by

$$\tilde{h} = \sigma h, \tag{10}$$

$$h(\tilde{\nabla}_X Y, Z) = h(\nabla_X Y, Z) - d(\ln \sigma)(Z) h(X, Y). \tag{11}$$

When there exists such a positive function σ that relates $(\mathcal{S}^n, \nabla, h)$ with $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$ as in (10) and (11), they are called 1-conformally equivalent and $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$ is also a statistical manifold [5].

2.3 A main result

Generally, the induced structure $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$ from the conformal divergence $\tilde{\rho}$ is not also dually flat, which is the most abundant structure in information geometry. However, by choosing the conformal factor σ carefully, we can demonstrate $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$ is dually flat. Hereafter, we call such a transformation as *conformal flattening.*

Define

$$Z(p) := \sum_{i=1}^{n+1} \nu_i(p) = \frac{1}{\Lambda(p)} \sum_{i=1}^{n+1} \frac{1}{L'(p_i)},$$

then it is negative because each $\nu_i(p)$ is. The conformal divergence to ρ with respect to the conformal factor $\sigma(r) := -1/Z(r)$ is

$$\tilde{\rho}(p, r) = -\frac{1}{Z(r)} \rho(p, r).$$

Proposition 1. *If the conformal factor is given by $\sigma = -1/Z$, then statistical manifold $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$ that is 1-conformally transformed from $(\mathcal{S}^n, \nabla, h)$ via (10) and (11) is dully flat. Further, $\tilde{\rho}$ is the canonical divergence where mutually dual pair of affine coordinates (θ^i, η_i) and a pair of potential functions (ψ, φ) are explicitly given by*

$$\theta^i(p) = x^i(p) - x^{n+1}(p) = L(p_i) - L(p_{n+1}), \quad i = 1, \cdots, n \tag{12}$$

$$\eta_i(p) = P_i(p) := \frac{\nu_i(p)}{Z(p)}, \quad i = 1, \cdots, n, \tag{13}$$

$$\psi(p) = -x_{n+1}(p) = -L(p_{n+1}), \tag{14}$$

$$\varphi(p) = \frac{1}{Z(p)} \sum_{i=1}^{n+1} \nu_i(p) x^i(p) = \sum_{i=1}^{n+1} P_i(p) L(p_i). \tag{15}$$

Proof) Using given relations, we first show that the conformal divergence $\tilde{\rho}$ is the canonical divergence for $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$:

$$\begin{aligned}
\tilde{\rho}(p,r) &= -\frac{1}{Z(r)}\langle \nu(r), f(p)-f(r)\rangle = \langle P(r), f(r)-f(p)\rangle \\
&= \sum_{i=1}^{n+1} P_i(r)(x^i(r)-x^i(p)) \\
&= \sum_{i=1}^{n+1} P_i(r)x^i(r) - \sum_{i=1}^{n} P_i(r)(x^i(p)-x^{n+1}(p)) - \left(\sum_{i=1}^{n+1} P_i(r)\right) x^{n+1}(p) \\
&= \varphi(r) - \sum_{i=1}^{n} \eta_i(r)\theta^i(p) + \psi(p). \qquad (16)
\end{aligned}$$

Next, let us confirm that $\partial\psi/\partial\theta^i = \eta_i$. Since $\theta^i(p) = L(p_i) + \psi(p),\ i = 1, \cdots, n$, we have

$$p_i = E(\theta^i - \psi), \quad i = 1, \cdots, n+1,$$

by setting $\theta^{n+1} := 0$. Hence, we have

$$1 = \sum_{i=1}^{n+1} E(\theta^i - \psi).$$

Differentiating by θ^j, we have

$$\begin{aligned}
0 &= \frac{\partial}{\partial\theta^j}\sum_{i=1}^{n+1} E(\theta^i-\psi) = \sum_{i=1}^{n+1} E'(\theta^i-\psi)\left(\delta^i_j - \frac{\partial\psi}{\partial\theta^j}\right) \\
&= E'(x^j) - \left(\sum_{i=1}^{n+1} E'(x^i)\right)\frac{\partial\psi}{\partial\theta^j}.
\end{aligned}$$

This implies that

$$\frac{\partial\psi}{\partial\theta^j} = \frac{E'(x^j)}{\sum_{i=1}^{n+1} E'(x^i)} = P_j = \eta_j.$$

Together with (16) and this relation, φ is confirmed to be the Legendre transform of ψ.

The dual relation $\partial\varphi/\partial\eta_i = \theta^i$ follows automatically from the property of the Legendre transform. Q.E.D.

Remark 2. Since the conformal metric is $\tilde{h} = -h/Z$, it is also positive definite. The dual affine connections ∇^* and $\tilde{\nabla}^*$ are projectively equivalent [5]. Hence, ∇^* is projectively flat. Further, the following corollary implies that the realized affine connection ∇ is also projectively equivalent to the flat connection $\tilde{\nabla}$ if we use the centro-affine immersion, i.e., $\xi^i = -L(p_i)$ [4, 5] (See also Appendix). Note that the expressions of the dual coordinates $\eta_i(p) = P_i(p)$ can be interpreted as generalization of the *escort probability* [12] (See the following example).

Corollary 1. *The choice of* ξ *does not affect on the obtained dually flat structure* $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$.

Proof) We have the following alternative expressions of $\eta_i = P_i$ with respect to L and E:

$$P_i(p) = \frac{1/L'(p_i)}{\displaystyle\sum_{k=1}^{n+1} 1/L'(p_k)} = \frac{E'(x_i)}{\displaystyle\sum_{i=1}^{n+1} E'(x_i)} > 0, \quad i = 1, \cdots, n.$$

Hence, all the expressions in proposition 1 does not depend on ξ, and the statement follows. Q.E.D.

2.4 Examples

If we take L to be the logarithmic function $L(t) = \ln(t)$, the conformally flattened geometry immediately defines the standard dually flat structure $(g^{\mathrm{F}}, \nabla^{(1)}, \nabla^{(-1)})$ on the simplex $\mathcal{S}^n$, where g^F denotes the Fisher metric. We see that $-\varphi(p)$ is the entropy, i.e., $\varphi(p) = \sum_{i=1}^{n+1} p_i \ln p_i$ and the conformal divergence is the KL divergence (relative entropy), i.e., $\tilde{\rho}(p, r) = D^{(\mathrm{KL})}(r||p) = \sum_{i=1}^{n+1} r_i(\ln r_i - \ln p_i)$.

Next let the affine immersion (f, ξ) be defined by the following L and ξ:

$$L(t) := \frac{1}{1-q} t^{1-q}, \quad x^i(p) = \frac{1}{1-q}(p_i)^{1-q},$$

and

$$\xi^i(p) = -q(1-q)x^i(p),$$

with $0 < q$ and $q \neq 1$, then it realizes the alpha-geometry [2] $(\mathcal{S}^n, \nabla^{(\alpha)}, g^F)$ with $q = (1+\alpha)/2$. Since the immersion (f, ξ) is centro-affine and the length of ξ is suitably scaled, $(\mathcal{S}^n, \nabla^{(\alpha)}, g^F)$ is of constant curvature $\kappa = (1-\alpha^2)/4$. The associated geometric divergence is the alpha-divergence, i.e.,

$$\rho(p, r) = D^{(\alpha)}(p, r) = \frac{4}{1-\alpha^2}\left(1 - \sum_{i=1}^{n+1} (p_i)^{(1-\alpha)/2}(r_i)^{(1+\alpha)/2}\right). \tag{17}$$

Following the procedure of conformally flattening described in the above, we have [10]

$$\Psi(x) = \sum_{i=1}^{n+1}((1-q)x^i)^{1/1-q}, \quad \Lambda(p) = -q, \ (constant)$$

$$\nu_i(p) = -\frac{1}{q}(p_i)^q, \quad -\frac{1}{Z(p)} = \frac{q}{\sum_{k=1}^{n+1}(p_i)^q},$$

and obtain dually flat structure $(\tilde{h}, \tilde{\nabla}, \tilde{\nabla}^*)$ via the formulas in proposition 1:

$$\eta_i = \frac{(p_i)^q}{\sum_{k=1}^{n+1}(p_k)^q}, \quad \theta^i = \frac{1}{1-q}(p_i)^{1-q} - \frac{1}{1-q}(p_{n+1})^{1-q} = \ln_q(p_i) - \psi(p),$$

$$\psi(p) = -\ln_q(p_{n+1}), \quad \varphi(p) = \ln_q \left(\frac{1}{\exp_q(S_q(p))} \right), \quad \tilde{h} = -\frac{1}{Z(p)} g^F.$$

Here, $\ln_q$ and $S_q(p)$ are the *q-logarithmic function* and the *Tsallis entropy* [12], respectively defined by

$$\ln_q(t) = \frac{t^{1-q} - 1}{1-q}, \quad S_q(p) = \frac{\sum_{i=1}^{n+1} (p_i)^q - 1}{1-q}.$$

3 Construction of Voronoi partitions and centroids with respect to geometric divergences

In the previous section we have seen that various geometric divergences ρ can be constructed on the statistical manifold $\mathcal{S}^n$ by changing the representing function L and the transversal vector field ξ.

We demonstrate an interesting application of the conformal flattening to topics related with computational geometry. We find escort probabilities (dual coordinates) play important roles. In this section, subscripts by Greek letters such as p_λ are used to denote the λ-th point in $\mathcal{S}^n$ among given ones while subscripts by Roman letters such as p_i denote the i-th coordinate of a point $p = (p_i) \in \mathcal{S}^n$.

3.1 Voronoi partitions

Let ρ be a geometric divergence defined in (6) on a 1-conformal statistical manifold $(\mathcal{S}^n, \nabla, h)$. For given m points $p_\lambda, \ \lambda = 1, \cdots, m$ on $\mathcal{S}^n$ we define *Voronoi regions* on $\mathcal{S}^n$ with respect to the geometric divergence ρ as follows:

$$\mathrm{Vor}^{(\rho)}(p_\lambda) := \bigcap_{\mu \neq \lambda} \{ r \in \mathcal{S}^n | \rho(p_\lambda, r) < \rho(p_\mu, r) \}, \quad \lambda = 1, \cdots, m.$$

An *Voronoi partition (diagram)* on $\mathcal{S}^n$ is a collection of the Voronoi regions and their boundaries. For example, if we take $L(t) = t^{1-q}/(1-q)$ as in section 2.4, the corresponding Voronoi partition is the one with respect to the alpha-divergence $D^{(\alpha)}$ in (17) on $(\mathcal{S}^n, \nabla^{(\alpha)}, g^F)$ [11]. Note that $D^{(\alpha)}$ approaches the Kullback-Leibler (KL) divergence if $\alpha \to -1$, and $D^{(0)}$ is called the Hellinger distance. Further, the partition is also equivalent to that with respect to *Rényi divergence* [14] defined by

$$D_\alpha(p, r) := \frac{1}{\alpha - 1} \ln \sum_{i=1}^{n+1} (p_i)^\alpha (r_i)^{1-\alpha}$$

because of their one-to-one functional relationship.

The standard algorithm using projection of a polyhedron [15, 16] commonly works well to construct Voronoi partitions for the Euclidean distance [16], the KL divergence [18]. The algorithm is generally applicable if a divergence function is of *Bregman type* [19], which is represented by the remainder of the first order Taylor expansion of a convex potential function in a suitable coordinate system. Geometrically speaking, this implies that

i) the divergence ρ is a canonical divergence associated with a dually flat structure, i.e, it is of Bregman type:

$$\begin{aligned}\rho(p,r) &= \psi(\theta(r)) + \varphi(\eta(r)) - \sum_{i=1}^{n} \theta^i(p)\eta_i(r) \\ &= \varphi(\eta(r)) - \left\{ \varphi(\eta(p)) + \sum_{i=1}^{n} \theta^i(p)\left(\eta_i(r) - \eta_i(p)\right) \right\}, \qquad (18) \\ \theta^i &= \frac{\partial \varphi(\eta)}{\partial \eta_i}, \quad i = 1, \cdots, n,\end{aligned}$$

ii) its affine coordinate system $\eta = (\eta_i)$ is chosen to realize the corresponding Voronoi partitions. In this coordinate system with one extra complementary coordinate the polyhedron is expressed as the upper envelop of m hyperplanes tangent to the potential function $\varphi(\eta)$ at $\eta(p_\lambda)$, $\lambda = 1, \cdots, m$.

A problem for the case of Voronoi partition with respect to geometric divergences ρ is that ρ on $\mathcal{S}^n$ is *not* generally of Bregman type, i.e., they *cannot* be represented as a remainder of any convex potentials as in (18).

The following theorem, however, claims that the problem is resolved by Proposition 1, i.e., conformally flattening a statistical manifold $(\mathcal{S}, \nabla, h)$ to a dually flat structure $(\mathcal{S}, \tilde{\nabla}, \tilde{h})$ and using the conformal divergence $\tilde{\rho}$, which is of Bregman type, and escort probabilities $\eta_i(p) = P_i(p)$ as a coordinate system.

The similar result is proved in [11] for the case of $D^{(\alpha)}$. However, the proof there was based on the fact that $(\mathcal{S}^n, \nabla^{(\alpha)}, g^F)$ is a statistical manifold of constant curvature and the modified Pythagorean relation (See Appendix) is used. In the following theorem, we prove with the usual Pythagorean relation on dually flat space and the assumption is relaxed to a 1-conformally flat statistical manifold $(\mathcal{S}, \nabla, h)$.

Here, we denote the space of escort distributions by $\mathcal{E}^n$ and represent the point on $\mathcal{E}^n$ by $P = (P_1, \cdots, P_n)$ because $P_{n+1} = 1 - \sum_{i=1}^{n} P_i$ and $\mathcal{E}^n$ is also the probability simplex.

Theorem 1. *i) The bisector of p_λ and p_μ defined by $\{r|\rho(p_\lambda, r) = \rho(p_\mu, r)\}$ is a simultaneously ∇^*- and $\tilde{\nabla}^*$-autoparallel hypersurface on $\mathcal{S}^n$.*

ii) Let $\mathcal{H}_\lambda, \lambda = 1, \cdots, m$ be the hyperplane in $\mathcal{E}^n \times \mathbf{R}$ which is respectively tangent at $(P(p_\lambda), \varphi(p_\lambda))$ to the hypersurface $\{(P, y) = (P(p), \varphi(p))|p \in \mathcal{S}^n\}$. The Voronoi partition with respect to ρ can be constructed on $\mathcal{E}^n$ by projecting the upper envelope of all $\mathcal{H}_\lambda$'s along the y-axis.

Proof. i) We construct a bisector for points p_λ and p_μ. Consider the $\tilde{\nabla}$-geodesic $\tilde{\gamma}$ connecting p_λ and p_μ, and let $\bar{p}$ be the midpoint on $\tilde{\gamma}$ satisfying $\tilde{\rho}(p_\lambda, \bar{p}) = \tilde{\rho}(p_\mu, \bar{p})$. Note that the point $\bar{p}$ satisfies $\rho(p_\lambda, \bar{p}) = \rho(p_\mu, \bar{p})$ by the conformal relation (9). Denote by $\mathcal{B}$ the $\tilde{\nabla}^*$-autoparallel hypersurface that is orthogonal to $\tilde{\gamma}$ at $\bar{p}$ with respect to the conformal metric $\tilde{h}$. Note that $\mathcal{B}$ is simultaneously ∇^*-autoparallel because of the projective equivalence of ∇^* and $\tilde{\nabla}^*$ as is mentioned in Remark 2.

Using these setup and the fact that $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$ is dually flat, we have the following relation from the Pythagorean theorem [2]

$$\tilde{\rho}(p_\lambda, r) = \tilde{\rho}(p_\lambda, \bar{p}) + \tilde{\rho}(\bar{p}, r) = \tilde{\rho}(p_\mu, \bar{p}) + \tilde{\rho}(\bar{p}, r) = \tilde{\rho}(p_\mu, r),$$

for all $r \in \mathcal{B}$. Using the conformal relation (9) again, we have $\rho(p_\lambda, r) = \rho(p_\mu, r)$ for all $r \in \mathcal{B}$. Hence, $\mathcal{B}$ is a bisector of p_λ and p_l.

ii) Recall the conformal relation (9) between ρ and $\tilde{\rho}$, then we see that $\mathrm{Vor}^{(\rho)}(p_\lambda) = \mathrm{Vor}^{(\mathrm{conf})}(p_\lambda)$ holds on $\mathcal{S}^n$, where

$$\mathrm{Vor}^{(\mathrm{conf})}(p_\lambda) := \bigcap_{\mu \neq \lambda} \{ r \in \mathcal{S}^n | \tilde{\rho}(p_\lambda, r) < \tilde{\rho}(p_\mu, r) \}.$$

Proposition 1 and the Legendre relations (16) imply that $\tilde{\rho}(p_\lambda, r)$ is represented with the escort probabilities, i.e., the dual coordinates $(P_i) = (\eta_i)$ by

$$\tilde{\rho}(p_\lambda, r) = \varphi(P(r)) - \left(\varphi(P(p_\lambda)) + \sum_{i=1}^{n} \frac{\partial \varphi}{\partial P_i}(p_\lambda) \{ P_i(r) - P_i(p_\lambda) \} \right),$$

By definition the hyperplane $\mathcal{H}_\lambda$ is expressed by

$$\mathcal{H}_\lambda = \left\{ (P(r), y(r)) \,\middle|\, y(r) = \varphi(P(p_\lambda)) + \sum_{i=1}^{n} \frac{\partial \psi^*}{\partial P_i}(p_\lambda) \{ P_i(r) - P_i(p_\lambda) \},\ r \in \mathcal{S}^n \right\}.$$

Hence, we have $\tilde{\rho}(p_\lambda, r) = \varphi(P(r)) - y(r)$. Thus, we see, for example, that the bisector on $\mathcal{E}^n$ for p_λ and p_μ is represented as a projection of $\mathcal{H}_\lambda \cap \mathcal{H}_\mu$. Thus, the statement follows. Q.E.D.

As a special case of the above theorem for $\rho = D^{(\alpha)}$, examples of Voronoi partitions with respect to $D^{(\alpha)}$ on usual probability simplex $\mathcal{S}^n$ and escort probability simplex $\mathcal{E}^n$ are compared in [11].

Remark 3. Voronoi partitions for broader class of divergences that are not necessarily associated with any convex potentials are theoretically studied [21] from more general affine differential geometric points of views.

On the other hand, the α-divergence can be expressed as a Bregman divergence if the domain is extended from $\mathcal{S}^n$ to the positive orthant $\mathbf{R}_+^{n+1}$.[1, 2, 24] Hence, the α-geometry on $\mathbf{R}_+^{n+1}$ is dually flat. Using this property, α-Voronoi partitions on $\mathbf{R}_+^{n+1}$ is discussed in [22].

However, while both of the above mentioned methods require constructions of the polyhedrons in the space of dimension $d = n + 2$, the new one proposed in this paper does in the space of dimension $d = n + 1$. Since it is known [23] that the optimal computational time of polyhedrons depends on the dimension d by $O(m \log m + m^{\lfloor d/2 \rfloor})$, the new one is better when n is even and m is large.

3.2 Weighted Centroids

Let $p_\lambda,\ \lambda = 1, \cdots, m$ be given m points on $\mathcal{S}^n$ and $w_\lambda > 0,\ \lambda = 1, \cdots, m$ be weights. Define the weighted *ρ-centroid* $c^{(\rho)} \in \mathcal{S}^n$ by the minimizer of the following problem:

$$\min_{p \in \mathcal{S}^n} \sum_{\lambda=1}^{m} w_\lambda \rho(p, p_\lambda).$$

Theorem 2. *The weighted ρ-centroid $c^{(\rho)}$ for given m points $p_1, \cdots, p_m$ on $\mathcal{S}^n$ is represented in weights w_λ, escort probabilities $P(p_\lambda)$ and the conformal factors $\sigma(p_\lambda) = -1/Z(p_\lambda) > 0$ by*

$$P_i(c^{(\rho)}) = \frac{1}{\sum_{\lambda=1}^{m} w_\lambda Z(p_\lambda)} \sum_{\lambda=1}^{m} w_\lambda Z(p_\lambda) P_i(p_\lambda), \quad i = 1, \cdots, n+1.$$

Proof. Denote $\theta^i(p)$ by θ^i simply. Using (9), we have

$$\begin{aligned}\sum_{\lambda=1}^{m} w_\lambda \rho(p, p_\lambda) &= -\sum_{\lambda=1}^{m} w_\lambda Z(p_\lambda) \tilde{\rho}(p, p_\lambda) \\ &= -\sum_{\lambda=1}^{m} w_\lambda Z(p_\lambda) \left\{ \psi(\theta) + \psi^*(\eta(p_\lambda)) - \sum_{i=1}^{n} \theta^i \eta_i(p_\lambda) \right\}.\end{aligned}$$

Then the optimality condition is

$$\frac{\partial}{\partial \theta^i} \sum_{\lambda=1}^{m} w_\lambda \rho(p, p_\lambda) = -\sum_{\lambda=1}^{m} w_\lambda Z(p_\lambda) \{\eta_i - \eta_i(p_\lambda)\} = 0, \quad i = 1, \cdots, n,$$

where $\eta_i = \eta_i(p)$. Thus, the statements for $i = 1, \cdots, n$ hold from $\eta_i = P_i$ in Proposition 1. For $i = n+1$, we have as follows:

$$\begin{aligned}P_{n+1}(c^{(\rho)}) &= 1 - \sum_{i=1}^{n} P_i(c^{(\rho)}) \\ &= \frac{1}{\sum_{\lambda=1}^{m} w_\lambda Z(p_\lambda)} \sum_{\lambda=1}^{m} w_\lambda Z(p_\lambda) \left\{ 1 - \sum_{i=1}^{n} P_i(p_\lambda) \right\} \\ &= \frac{1}{\sum_{\lambda=1}^{m} w_\lambda Z(p_\lambda)} \sum_{\lambda=1}^{m} w_\lambda Z(p_\lambda) P_{n+1}(p_\lambda).\end{aligned}$$

Q.E.D.

4 Concluding remarks

We have realized 1-conformally flat structures $(\mathcal{S}^n, \nabla, h)$ by changing affine immersions (f, ξ) or representing functions L, and discussed their conformal flattening. Applications of the result to the topics in computational geometry are also discussed. Conformal divergences of Bregman-type divergences and their properties are also exploited in [25] from different points of views.

Extension to the other statistical model such as a family of continuous probability distributions would be in the future work. While relations with the gradient flows (replicator flows, in a special case) on $(\mathcal{S}^n, \nabla, h)$ or $(\mathcal{S}^n, \tilde{\nabla}, \tilde{h})$ can be found in [26], searching for the other applications of the technique would be of interest.

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A Appendix: statistical manifolds and affine differentail geometry

We shortly summarize the basic notions and results in information geometry [1, 2], Hessian domain [3] and affine differential geometry [4, 5], which are used in this paper. See for the details and proofs in the literature.

A.1 Statistical manifolds

For a torsion-free affine connection ∇ and a pseudo-Riemannian metric g on a manifold $\mathcal{M}$, the triple $(\mathcal{M}, \nabla, g)$ is called a *statistical (Codazzi) manifold* if it admits another torsion-free connection ∇^* satisfying

$$Xg(Y, Z) = g(\nabla_X Y, Z) + g(Y, \nabla^*_X Z) \tag{19}$$

for arbitrary X, Y and Z in $\mathcal{X}(\mathcal{M})$, where $\mathcal{X}(\mathcal{M})$ is the set of all tangent vector fields on $\mathcal{M}$. We say that ∇ and ∇^* *duals* of each other with respect to g, and (g, ∇, ∇^*) is called *dualistic structure* on $\mathcal{M}$.

A statistical manifold $(\mathcal{M}, \nabla, g)$ is said to be of *constant curvature* $\kappa \in \mathbf{R}$ if the curvature tensor R of ∇ satisfies

$$R(X, Y)Z = \kappa\{g(Y, Z)X - g(X, Z)Y\}. \tag{20}$$

When the constant κ is zero, the statistical manifold is called *flat*, or *dually flat*, because the dual curvature tensor R^* of ∇^* also vanishes automatically [2, 3].

For $\alpha \in \mathbf{R}$, statistical manifolds $(\mathcal{M}, \nabla, g)$ and $(\mathcal{M}, \tilde{\nabla}, \tilde{g})$ are said to be *α-conformally equivalent* [5] if there exists a positive function σ on $\mathcal{M}$ satisfying

$$\begin{aligned}
\tilde{g}(X,Y) &= \sigma g(X,Y) \\
g(\tilde{\nabla}_X Y, Z) &= g(\nabla_X Y, Z) - \frac{1+\alpha}{2}(d\ln\sigma)(Z)g(X,Y) \\
&\quad + \frac{1-\alpha}{2}\{(d\ln\sigma)(X)g(Y,Z) + (d\ln\sigma)(Y)g(X,Z)\}.
\end{aligned}$$

Statistical manifolds $(\mathcal{M}, \nabla, g)$ and $(\mathcal{M}, \tilde{\nabla}, \tilde{g})$ are α-conformally equivalent if and only if $(\mathcal{M}, \nabla^*, g)$ and $(\mathcal{M}, \tilde{\nabla}^*, \tilde{g})$ are $-\alpha$-conformally equivalent. In particular, -1-conformal equivalence means *projective equivalence* of ∇ and $\tilde{\nabla}$, which implies that a ∇-pregeodesic curve is simultaneously $\tilde{\nabla}$-pregeodesic [4]. A statistical manifold $(\mathcal{M}, \nabla, g)$ is called *α-conformally flat* if it is locally α-conformally equivalent to a flat statistical manifold. It is known that a statistical manifold is of constant curvature if and only if it is ± 1-conformally flat, when $\dim \mathcal{M} \geq 3$ [5].

A.2 Affine differential geometry

Let $\mathcal{M}$ be an n-dimensional manifold and consider an *affine immersion* [4] (f, ξ), which is the pair of an immersion f from $\mathcal{M}$ into $\mathbf{R}^{n+1}$ and a transversal vector field ξ along $f(\mathcal{M})$. By a given affine immersion (f, ξ) of $\mathcal{M}$ and the usual flat affine connection D of $\mathbf{R}^{n+1}$, the Gauss and Weingarten formulas are respectively obtained as follows:

$$\begin{aligned}
D_X f_*(Y) &= f_*(\nabla_X Y) + h(X,Y)\xi, \\
D_X \xi &= -f_*(SX) + \tau(X)\xi.
\end{aligned}$$

Here, ∇, h, S and τ are called, respectively, *induced connection, affine fundamental form, affine shape operator* and *transversal connection form.* In this case, we say the affine immersion realizes $(\mathcal{M}, \nabla, h)$ in $\mathbf{R}^{n+1}$. If h is non-degenerate (resp. $\tau = 0$ on $\mathcal{M}$), the affine immersion (f, ξ) is called *non-degenerate* (resp. *equiaffine*). It is known that non-degenerate and equiaffine (f, ξ) realizes a statistical manifold $(\mathcal{M}, \nabla, h)$ by regarding h as a pseudo-Riemannian metric g.

Such a statistical manifold is characterized as follows:

Proposition 2. *[5] A simply connected statistical manifold $(\mathcal{M}, \nabla, g)$ can be realized by a non-degenerate and equiaffine immersion if and only if it is 1-conformally flat.*

Let a point o be fixed as an origin of $\mathbf{R}^{n+1}$ and f be an immersion from $\mathcal{M}$ to $\mathbf{R}^{n+1} \backslash \{o\}$. For $p \in \mathcal{M}$ take $\xi = -\overrightarrow{of(p)}$, then ξ is transversal to $f(\mathcal{M})$. For such an affine immersion (f, ξ) is called *centro-affine*, where the Weingarten formula is $D_X \xi = -f_*(X)$, or $S = I$ and $\tau = 0$. This implies that a centro-affine immersion, if it is non-degenerate, realizes an statistical manifold of constant curvature because of the Gauss equation:

$$R(X,Y)Z = h(X,Z)SX - h(X,Z)SY.$$

Further, the realized affine connection ∇ is projectively flat [4].

Denote the dual space of $\mathbf{R}^{n+1}$ by $\mathbf{R}_{n+1}$ and the pairing of $x \in \mathbf{R}^{n+1}$ and $y \in \mathbf{R}_{n+1}$ by $\langle y, x\rangle$. Define a map $\nu : \mathcal{M} \to \mathbf{R}_{n+1}\backslash\{o\}$ as follows:

$$\langle \nu_p, \xi_p\rangle = 1, \quad \langle \nu_p, f_*(X)\rangle = 0 \quad (\forall X \in T_p\mathcal{M}).$$

Such ν_p is uniquely defined and is called the *conormal vector*.

The pair $(\nu, -\nu)$ can be regarded as a centro-affine immersion into the dual space $\mathbf{R}_{n+1}$ equipped with the usual flat connection D^*. The formulas are

$$\begin{aligned} D^*_X(\nu_* Y) &= \nu(\nabla^*_X Y) + h^*(X,Y)(-\nu), \\ D^*_X(-\nu) &= -\nu_*(X), \end{aligned}$$

where $h^*(X,Y) = h(SX,Y)$, and ∇^* is dual of ∇ with respect to h. Hence, when (f,ξ) realizes a statistical manifold $(\mathcal{M}.\nabla, h)$ with $S = I$, then $(\nu, -\nu)$ realizes its dual statistical manifold $(\mathcal{M}, \nabla^*, h)$ [4]. Both manifolds are of constant curvature.

For a statistical manifold $(\mathcal{M}, \nabla, h)$ realized by a non-degenerate and equiaffine immersion (f,ξ), we can define a *contrast function* ρ that induces the structure $(\mathcal{M}, \nabla, h)$

$$\rho(p,q) = \langle \nu(q), f(p) - f(q)\rangle, \quad (p, q \in \mathcal{M}).$$

For a statistical manifold $(\mathcal{M}, \tilde{\nabla}, \tilde{h})$ that is 1-conformally equivalent to $(\mathcal{M}, \nabla, h)$, one of its contrast function is given by $\tilde{\rho}(p,q) = \sigma(q)\rho(p,q)$ for a certain positive function σ [5]. Contrast functions ρ and $\tilde{\rho}$ are called *geometric divergence* and *conformal divergence*, respectively.

A statistical manifold $(\mathcal{M}, \nabla, g)$ of constant curvature κ is studied from viewpoint of affine differential geometry [5]. It is known that $(\mathcal{M}, \nabla, g)$ realized in $\mathbf{R}^{n+1}$ has the following geometric properties:

P1 For the right triangle with ∇-geodesic and ∇^*-geodesic, the following modified Pythagorean relation holds on $\mathcal{M}$:

$$\rho(p,r) = \rho(p,q) + \rho(q,r) - \kappa\rho(p,q)\rho(q,r)$$

P2 An arbitrary ∇-geodesic on $\mathcal{M}$ is the intersection of a two-dimensional subspace in $\mathbf{R}^{n+1}$ and $\mathcal{M}$,

P3 The induced volume element θ from $\mathbf{R}^{n+1}$ satisfies $\nabla\theta = 0$,

and so on. A typical example of the statistical manifold of non-zero constant curvature is the alpha-geometry $(\mathcal{S}^n, \nabla^{(\alpha)}, g^F)$, where $\kappa = (1-\alpha^2)/4$ and the modified Pythagorean relation induces nonextensivity relation of Tsallis entropy [24].