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Anisotropic convexified Gauss curvature flow of bounded open sets:
stochastic approximation, weak solution and viscosity solution

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1 Introduction

Gauss curvature flow is known as a mathematical model of the wearing process of a convex stone rolling on a beach (see [2]).

In [3] we proposed and studied a two dimensional random crystalline algorithm for the curvature flow of smooth simple closed convex curves.

In [4] we studied a convexified Gauss curvature flow of compact sets by the level set approach in the theory of viscosity solutions.

In this talk we discuss a random crystalline algorithm of and PDE on an anisotropic convexified Gauss curvature flow of bounded open sets in \mathbf{R}^N for **any** $N \geq 2$ (see [5]).

We introduce an assumption and a notation before we describe the PDE under consideration.

$$(A.1). \ R \in L^1(\mathbf{S}^{N-1} : [0, \infty), d\mathcal{H}^{N-1}), \text{ and } \|R\|_{L^1(\mathbf{S}^{N-1})} = 1.$$

For $p \in \mathbf{R}^N$ and a $N \times N$ -symmetric real matrix X , put $G(o, X) := 0$ and

$$G(p, X) := |p| \det_+ \left(-\left(I - \frac{p}{|p|} \otimes \frac{p}{|p|}\right) \frac{X}{|p|} \left(I - \frac{p}{|p|} \otimes \frac{p}{|p|}\right) + \frac{p}{|p|} \otimes \frac{p}{|p|} \right)$$

if $p \neq o$.

We study a weak solution and a viscosity solution of the following PDE in this talk:

$$\partial_t u(t, x) = \sigma^+(u, Du(t, x), t, x) R\left(\frac{Du(t, x)}{|Du(t, x)|}\right) G(Du(t, x), D^2u(t, x)) \quad (1.1)$$

$((t, x) \in (0, \infty) \times \mathbf{R}^N)$. Here

$$\sigma^+(u, p, t, x) := \begin{cases} 1 & \text{if } u(t, \cdot) \leq u(t, x) \text{ on } H(p, x) \text{ and } p \in \mathbf{R}^N \setminus \{o\}, \\ 0 & \text{otherwise,} \end{cases}$$

$$H(p, x) := \{y \in \mathbf{R}^N \setminus \{x\} \mid \langle y - x, p \rangle \leq 0\}.$$

To introduce the notion of a weak solution to (1.1), we give several notations.

Let F be a closed convex subset of \mathbf{R}^N . For $x \in \partial F$, put

$$N_F(x) := \{p \in \mathbf{S}^{N-1} \mid F \subset \{y \mid \langle y - x, p \rangle \leq 0\}\}.$$

Definition 1 Suppose that (A.1) holds. Let $u : \mathcal{D}(u) (\subset \mathbf{R}^N) \mapsto \mathbf{R}$ be bounded and $r \in \mathbf{R}$. For any $B \in B(\mathbf{R}^N)$, put

$$\omega_r(R, u, B) := \int_{N_{(co \ u^{-1}([r, \infty))) - (B \cap \partial(co \ u^{-1}([r, \infty)))}} R(p) d\mathcal{H}^{N-1}(p),$$

$$\mathbf{w}(R, u, B) := \int_{\mathbf{R}} dr \omega_r(R, u, B),$$

provided the right hand side is well defined.

Definition 2 (Weak Solutions) Suppose that (A.1) holds.

(i) A family of bounded open sets $\{D(t)\}_{t \geq 0}$ in \mathbf{R}^N is called an anisotropic convexified Gauss curvature flow if

$$D(t) = \begin{cases} (co \ D(t)) \cap D(0) & \text{for } t \in [0, Vol(D)), \\ \emptyset & \text{for } t \geq Vol(D) \end{cases} \quad (1.2)$$

; and for any $\varphi \in C_o(\mathbf{R}^N)$ and any $t \geq 0$,

$$\int_{\mathbf{R}^N} \varphi(x) (I_{D(0)}(x) - I_{D(t)}(x)) dx = \int_0^t ds \int_{\mathbf{R}^N} \varphi(x) \omega_1(I_{D(s)}(\cdot), dx). \quad (1.3)$$

(ii) $u \in C_b([0, \infty) \times \mathbf{R}^N)$ is called the weak solution to (1.1) if the following holds: for any $\varphi \in C_o(\mathbf{R}^N)$ and any $t \geq 0$,

$$\int_{\mathbf{R}^N} \varphi(x) (u(0, x) - u(t, x)) dx = \int_0^t ds \int_{\mathbf{R}^N} \varphi(x) \mathbf{w}(u(s, \cdot), dx). \quad (1.4)$$

Before we introduce the notion of a viscosity solution to (1.1), we introduce notations

$f \in \mathcal{F}$ iff $f \in C^2([0, \infty))$, $f''(r) > 0$ on $(0, \infty)$, and $f(r)/r^N \rightarrow 0$ as $r \rightarrow 0$.

Let Ω be an open subset of $(0, \infty) \times \mathbf{R}^N$. $f \in \mathcal{A}(\Omega)$ iff $\varphi \in C^2(\Omega)$, and for any $(\hat{t}, \hat{x}) \in \Omega$ for which $D\varphi$ vanishes, there exists $f \in \mathcal{F}$ such that

$$|\varphi(t, x) - \varphi(\hat{t}, \hat{x}) - \partial_t \varphi(\hat{t}, \hat{x})(t - \hat{t})| \leq f(|x - \hat{x}|) + o(|t - \hat{t}|) \quad \text{as } (t, x) \rightarrow (\hat{t}, \hat{x}).$$

Definition 3 (Viscosity solution) (see [6]).

Let $0 < T \leq \infty$ and set $\Omega := (0, T) \times \mathbf{R}^N$.

(i). A function $u \in USC(\Omega)$ is called a viscosity subsolution of (1.1) in Ω if whenever $\varphi \in \mathcal{A}(\Omega)$, $(s, y) \in \Omega$, and $u - \varphi$ attains a local maximum at (s, y) , then

$$\partial_t \varphi(s, y) + \sigma^-(u, D\varphi(s, y), s, y) R\left(\frac{D\varphi(s, y)}{|D\varphi(s, y)|}\right) G(D\varphi(s, y), D^2\varphi(s, y)) \leq 0, \quad (1.5)$$

where

$$\sigma^-(u, p, s, y) := \begin{cases} 1 & \text{if } u(s, \cdot) < u(s, y) \text{ on } H(p, y) \text{ and } p \in \mathbf{R}^N \setminus \{o\}, \\ 0 & \text{otherwise.} \end{cases}$$

(ii). A function $u \in LSC(\Omega)$ is called a viscosity supersolution of (1.1) in Ω if whenever $\varphi \in \mathcal{A}(\Omega)$, $(s, y) \in \Omega$, and $u - \varphi$ attains a local minimum at (s, y) , then

$$\partial_t \varphi(s, y) + \sigma^+(u, D\varphi(s, y), s, y) R\left(\frac{D\varphi(s, y)}{|D\varphi(s, y)|}\right) G(D\varphi(s, y), D^2\varphi(s, y)) \geq 0. \quad (1.6)$$

(iii). A function $u \in C(\Omega)$ is called a viscosity solution of (1.1) in Ω if it is both a viscosity subsolution and a supersolution of (1.1) in Ω .

Next we introduce a class of stochastic processes of which continuum limit becomes an anisotropic convexified Gauss curvature flow.

The following is an assumption on the initial set.

(A.2). D is a bounded open set in \mathbf{R}^N such that $\text{Vol}(\partial D) = 0$.

Take $K > 0$ so that $\text{co } D \subset [-K + 1, K - 1]^N$. Put

$$\mathcal{S}_n := \{I_A : [-K, K]^N \cap (\mathbf{Z}^N/n) \mapsto \{0, 1\} | A \subset \mathbf{Z}^N/n\}.$$

For $x, z \in \mathbf{Z}^N/n$ and $v \in \mathcal{S}_n$, put

$$v_{n,z}(x) := \begin{cases} v(x) & \text{if } x \neq z, \\ 0 & \text{if } x = z \end{cases}$$

; and for a bounded $f : \mathcal{S}_n \mapsto \mathbf{R}$, put

$$A_n f(v) := n^N \sum_{z \in [-K, K]^N \cap (\mathbf{Z}^N/n)} \omega_1(R, v, \{z\}) \{f(v_{n,z}) - f(v)\}.$$

Let $\{Y_n(t, \cdot)\}_{t \geq 0}$ be a Markov process on \mathcal{S}_n ($n \geq 1$), with the generator A_n , such that $Y_n(0, z) = I_{D^c \cap (\mathbf{Z}^N/n)}(z)$.

For $(t, x) \in [0, \infty) \times [-K, K]^N$, put also

$$D_n(t) := (\text{co } Y_n(t, \cdot)^{-1}(1))^o \cap D. \quad (1.7)$$

$$X_n(t, x) := I_{D_n(t)}(x). \quad (1.8)$$

Then $\{X_n(t, \cdot)\}_{t \geq 0}$ is a stochastic process on

$$\mathcal{S} := \{f \in L^2([-K, K]^N) : \|f\|_{L^2([-K, K]^N)} \leq (2K)^N\}$$

which is a complete separable metric space by the metric

$$d(f, g) := \sum_{k=1}^{\infty} \frac{\max(|\langle f - g, e_k \rangle_{L^2([-K, K]^N)}|, 1)}{2^k}.$$

Here $\{e_k\}_{k \geq 1}$ denotes a complete orthonormal basis of $L^2([-K, K]^N)$.

By definition, the following holds.

- (1) $D_n(0) \rightarrow D$ in Hausdorff metric as $n \rightarrow \infty$.
- (2) $\sum_{z \in (\mathbf{Z}^N/n) \cap [-K, K]^N} |I_{D_n(t)}(z) - I_{D_n(t-)}(z)| = 0$ or 1 for all $t \geq 0$.
- (3) If $|I_{D_n(t)}(z) - I_{D_n(t-)}(z)| = 1$, then $z \in \partial(\text{co } D_n(t-))$.
- (4) $\sum_{z \in (\mathbf{Z}^N/n) \cap [-K, K]^N} |I_{D_n(t)}(z) - I_{D_n(t-)}(z)| = 1$ if and only if $t = \sigma_{n,i}$ for some i , where $0 < \sigma_{n,1} < \sigma_{n,1} < \dots$ are random variables such that $\{\sigma_{n,i+1} - \sigma_{n,i}\}_{i \geq 0}$ are independent and that

$$P(\sigma_{n,i+1} - \sigma_{n,i} \in dt) = n^N \exp(-n^N t) dt.$$

- (5) $P(I_{D_n(\sigma_{n,i})}(z) - I_{D_n(\sigma_{n,i}-)}(z) = 1) = E[\omega_1(R, I_{D_n(\sigma_{n,i}-)}, \{z\})]$.

2 Main result

In this section we give our main result from [5].

The following theorem implies that D_n is a random crystalline approximation of an anisotropic convexified Gauss curvature flow.

Theorem 1 *Suppose that (A.1)-(A.2) hold. Then there exists a unique anisotropic convexified Gauss curvature flow $\{D(t)\}_{t \geq 0}$ with $D(0) = D$, and for any $\gamma > 0$,*

$$\lim_{n \rightarrow \infty} P(\sup_{0 \leq t} \|X_n(t, \cdot) - I_{D(t)}(\cdot)\|_{L^2([-K, K]^N)} \geq \gamma) = 0. \quad (2.1)$$

Suppose in addition that D is convex. Then for any $T \in [0, \text{Vol}(D))$ and $\gamma > 0$,

$$\lim_{n \rightarrow \infty} P(\sup_{0 \leq t \leq T} d_H(D_n(t), D(t)) \geq \gamma) = 0, \quad (2.2)$$

where d_H denotes Hausdorff metric.

We introduce an additional assumption.

(A.3). $h \in C_b(\mathbf{R}^N)$ and for any $r \in \mathbf{R}$, the set $h^{-1}((r, \infty))$ is bounded or \mathbf{R}^N .

The following corollary implies that a level set of a continuous weak solution to (1.1) is determined by that at $t = 0$.

Corollary 1 *Suppose that (A.1) and (A.3) hold. Then there exists a unique bounded continuous weak solution $\{u(t, \cdot)\}_{t \geq 0}$ to (1.1) and for any $r \in \mathbf{R}$, $\{u(t, \cdot)^{-1}((r, \infty))\}_{t \geq 0}$ is a unique anisotropic convexified Gauss curvature flow with initial data $u(0, \cdot)^{-1}((r, \infty))$.*

We state properties of anisotropic convexified Gauss curvature flows.

Theorem 2 *Suppose that (A.1)-(A.2) hold. Let $\{D(t)\}_{t \geq 0}$ be a unique anisotropic convexified Gauss curvature flow $\{D(t)\}_{t \geq 0}$ with $D(0) = D$. Then*

- (a) $t \mapsto D(t)$ is nonincreasing on $[0, \infty)$.
- (b) For any $t \leq T^* := \text{Vol}(D(0))$,

$$\text{Vol}(D(0) \setminus D(t)) = t. \quad (2.3)$$

(c) Let $\{D_1(t)\}_{t \geq 0}$ be an anisotropic convexified Gauss curvature flow such that $D_1(0)$ is a bounded, convex, open set which contains D . Then

$$D(t) \subset D_1(t) \quad \text{for all } t \geq 0, \quad (2.4)$$

where the equality holds if and only if $D(0) = D_1(0)$.

We give an additional assumption and state the result on viscosity solutions to (1.1).

$$(A.4). \quad R \in C(S^{N-1} : [0, \infty)).$$

Theorem 3 *Suppose that (A.2) and (A.4) hold. Let $\{D(t)\}_{t \geq 0}$ be a unique anisotropic convexified Gauss curvature flow $\{D(t)\}_{t \geq 0}$ with $D(0) = D$. Then $I_{D(t)}(x)$ and $I_{D(t)-}(x)$ are a viscosity supersolution and a viscosity subsolution to (1.1), respectively.*

The following results imply that $u \in C_b([0, \infty) \times \mathbf{R}^N)$ is a weak solution to (1.1) if and only if it is a viscosity solution to (1.1), in case R is constant.

Corollary 2 *Suppose that (A.3)-(A.4) hold. Then a unique weak solution $u \in C_b([0, \infty) \times \mathbf{R}^N)$ to (1.1) is a viscosity solution to it.*

Corollary 3 *(see [4]) Suppose that (A.3) holds and that R is constant. Then a continuous viscosity solution to (1.1) is unique and is a weak solution to it.*

3 Sketch of Proof

(Idea of Proof of Theorem 1). We first show that $\{X_n(t, \cdot)\}_{t \geq 0}$ is tight in $D([0, \infty) : \mathcal{S})$. By the weak convergence result on ω_1 by Bakelman [1], we show that any weak limit point of $\{X_n(t, \cdot)\}_{t \geq 0}$ is a weak solution to (1.1).

The following lemma implies the uniqueness, and hence completes the proof.

Lemma 1 *Suppose that (A.1) hold. If $\{I_{D_i(t)}\}_{t \geq 0}$ ($i = 1, 2$) are weak solutions to (1.1) for which $D_1(0) \subset D_2(0)$, then $D_1(t) \subset D_2(t)$ for all $t \geq 0$. In particular,*

$$d(D_1(t), D_2(t)^c) \geq d(D_1(0), D_2(0)^c), \quad (3.1)$$

for $t \leq \text{Vol}(D_1(0))$.

(Sketch of Proof of Corollary 1). For $r \in \mathbf{R}$, let $\{I_{D_r(t)}\}_{t \geq 0}$ denote a unique weak solution of (1.1) with $D_r(0) = h^{-1}((r, \infty))$.

Put

$$u(t, x) := \sup\{r \in \mathbf{R} | x \in D_r(t)\}.$$

Then u is continuous. In particular, for all $t \geq 0$ and $r \in \mathbf{R}$,

$$u(t, \cdot)^{-1}((r, \infty)) = D_r(t).$$

For $n \geq 1$, put $k_{n,1} := [n \sup\{h(y) | y \in \mathbf{R}^N\}]$ and $k_{n,0} := [n \inf\{h(y) | y \in \mathbf{R}^N\}]$. Then for any $\varphi \in C_o(\mathbf{R}^N)$ and any $t \geq 0$,

$$\begin{aligned}
& \int_{\mathbf{R}^N} \varphi(x) \left[\sum_{k_{n,0} \leq k \leq k_{n,1}} \frac{k}{n} (I_{D_{\frac{k}{n}}(t)^c}(x) - I_{D_{\frac{k+1}{n}}(t)^c}(x)) \right. \\
& \quad \left. - \sum_{k_{n,0} \leq k \leq k_{n,1}} \frac{k}{n} (I_{D_{\frac{k}{n}}(0)^c}(x) - I_{D_{\frac{k+1}{n}}(0)^c}(x)) \right] dx \\
&= \int_0^t ds \left[\sum_{k_{n,0} < k \leq k_{n,1}} \frac{1}{n} \int_{\mathbf{R}^N} \varphi(x) \omega_0(R, I_{D_{\frac{k}{n}}(s)^c}(\cdot), dx) \right].
\end{aligned}$$

Letting $n \rightarrow \infty$ in (3.4), u is shown to be a weak solution to (1.1).

The uniqueness of u follows from that of $D_r(\cdot)$ for all r . In fact we can show that for a continuous weak solution v to (1.1), $\{v(t, \cdot)^{-1}((r, \infty))\}_{t \geq 0}$ is an anisotropic convexified Gauss curvature flow.

Q. E. D.

We omit the proof of Theorems 2 and 3.

(Sketch of Proof of Corollary 2)

Let u be a weak solution to (1.1).

We first show that u is a viscosity supersolution to (1.1). Suppose that u is smooth in Ω and that $\varphi \in \mathcal{A}(\Omega)$, $(s, y) \in \Omega$, and $u - \varphi$ attains a local maximum at (s, y) . Then

$$\partial_s(u - \varphi)(s, y) \geq 0.$$

$$\partial_s(u - \varphi^\varepsilon)(s, y) \geq 0$$

($\varepsilon > 0$), where $\varphi^\varepsilon := \varphi - \varepsilon$. Hence formally, we have, in some neighborhood of (s, y) ,

$$\begin{aligned}
& \partial_s \varphi^\varepsilon(t, x) \\
& \leq \partial_s u(t, x) = -\mathbf{w}(u(t, \cdot), dx)/dx \\
& \leq -\mathbf{w}(\varphi^\varepsilon(t, \cdot), dx)/dx = -R\left(\frac{D\varphi(t, x)}{|D\varphi(t, x)|}\right)G(D\varphi(t, x), D^2\varphi(t, x)).
\end{aligned}$$

Then following lemma completes the proof.

Take $\varphi \in C^2(\mathbf{R}^N : \mathbf{R})$ for which $D\varphi(x_o) \neq 0$ for some $x_o \in \mathbf{R}^N$. For $i = 1, \dots, N$, put

$$y_i(x) := \left(-(1 - \delta_{ij}) \frac{\partial_j \varphi(x)}{|D\varphi(x)|} + \delta_{ij} \varphi(x) \right)_{j=1}^N.$$

Then

Lemma 2 *Suppose that all eigenvalues of $-D(D\varphi(x_o)/|D\varphi(x_o)|)$ are non-negative. Then, for $i = 1, \dots, N$,*

$$\frac{\partial_i \varphi(x_o)}{|D\varphi(x_o)|} G(D\varphi(x_o), D^2\varphi(x_o)) = \det(Dy_i(x_o)). \quad (3.2)$$

Similarly one can show that u is a viscosity subsolution to (1.1).

Q. E. D.

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