CONVERGENCE OF MEAN CURVATURE FLOWS WITH SURGERY

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Abstract. Huisken and Sinestrari [8] have recently defined a surgery process for mean curvature flow when the initial data is a two-convex hypersurface in $\mathbb{R}^{n+1}$ ($n \geq 3$). The process depends on a parameter $H$. Its role is to initiate a surgery when the maximum of the mean curvature of the evolving hypersurface becomes $H$, and to control the scale at which each surgery is performed. We prove that as $H \to \infty$ the surgery process converges to level set flow [1] [2].

Introduction

Huisken and Sinestrari [8] have recently defined a mean curvature flow with surgery when the initial data is a two-convex hypersurface in $\mathbb{R}^{n+1}$ when $n \geq 3$. The process depends on a parameter $H$ ($H_3$ in the notation of [8]), which controls both the maximal mean curvature and the scale at which each surgery is performed. In this note we investigate to what extent the process depends on this parameter.

Recall that a smooth one-parameter family of hypersurface immersions $F_t : M \to \mathbb{R}^{n+1}$ is a solution to mean curvature flow if

$$\frac{\partial F}{\partial t}(x,t) = \vec{H}(F(x,t)),$$

where $\vec{H}$ is the mean curvature vector. The first results were obtained by Huisken [7] who proved that if the initial data is convex and $n \geq 2$, then the mean curvature flow shrinks the hypersurface to a round point. The analogous result for curves in the plane ($n = 1$) was proved by Gage and Hamilton [3], and shortly after Grayson [4] showed that any embedded curve in the plane evolves to become convex. This means that the classification of singularities is particularly simple for embedded plane curves. However, when $n > 1$ Grayson’s Theorem no longer holds and singularities other than round points may occur. The existence of such a singularity was first proved rigourously by Grayson [5], who gave the example of a barbell-like surface which develops a neck-pin.

As an evolving hypersurface becomes singular the maximum of the mean curvature is unbounded, and hence constructing a surgery procedure requires detailed information about the geometry of the hypersurface in regions of high curvature. In the two-convex case,
Huisken and Sinestrari prove that such regions are diffeomorphic to $S^n$ or $S^{n-1} \times S^1$, and are discarded during surgery, or are neck-like regions in which the surgery replaces a topological cylinder by a pair of convex disks. As the parameter $H$ increases the surgeries are performed closer to the singular time and on quantitatively thinner necks. The detailed estimates in [8] controlling the length and width of the necks allow us to prove:

**Theorem A.** As $H \to \infty$ the Huisken-Sinestrari surgery converges to level set flow.

Since the limit is unique this result can be interpreted as a stability theorem for level set flow. Our approach is to use a barrier argument: We prove that for any $\epsilon > 0$ there exists $H > 0$ so that the mean curvature flow with surgery performed with parameter $H$ is disjoint (in space-time) from the level set flow of the initial hypersurface shifted backwards in time by $\epsilon$.

Since the Ricci flow with surgery constructed for 3-manifolds (see [10] and [11]) also depends on a parameter, it is possible to consider the same question there. One obstacle in this direction is that there is no natural candidate for the limiting object.

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1. **Weak notions of mean curvature flow**

In this section we recall (see [8] [9] [12]) two ways in which the evolution of a smooth hypersurface can be extended beyond a singularity: Level set flow and mean curvature flow with surgery.

**Definition 1.1** (Weak Set Flow). Let $K \subset \mathbb{R}^{n+1}$ be closed, and let $\{K_t\}_{t \geq 0}$ be a one-parameter family of closed sets with initial condition $K_0 = K$ such that the space-time track $\bigcup (K_t \times \{t\}) \subset \mathbb{R}^{n+2}$ is closed. Then $\{K_t\}_{t \geq 0}$ is weak set flow for $K$ if for every smooth mean curvature flow $\Sigma_t$ defined on $[a, b]$ we have

$$K_a \cap \Sigma_a = \emptyset \implies K_t \cap \Sigma_t = \emptyset$$

for each $t \in [a, b]$.

It is essentially the definition that weak set flows avoid smooth mean curvature flows when the initial conditions are disjoint but a stronger statement is true: The distance between a weak set flow and a smooth mean curvature flow is nondecreasing in $t$. Otherwise one could translate the initial data in space and obtain a contradiction to the definition of a weak set flow.

**Definition 1.2** (Level Set Flow). The level set flow of a compact set $K \subset \mathbb{R}^{n+1}$, denoted $LSF(K)$, is the maximal weak set flow. That is, a one-parameter family of closed sets $K_t$ with $K_0 = K$ such that if $\tilde{K}_t$ is any weak set flow with $\tilde{K}_0 = K$ then $\tilde{K}_t \subset K_t$ for each $t \geq 0$. 
The existence of a maximal weak set flow is verified by taking the closure of the union of all weak set flows with a given initial data. If $K_t$ is the weak set flow of $K$, we denote by $\hat{K}$ by the space-time track swept out by $K_t$. That is,

$$\hat{K} = \bigcup_{t \geq 0} K_t \times \{t\} \subset \mathbb{R}^{n+2}.$$ 

The level set flow was introduced independently by Evans and Spruck [2] and Chen, Giga and Goto [1]. It was first formulated in terms of viscosity solutions of partial differential equations whereas the geometric definition above was first used by Ilmanen [9].

Another approach to constructing weak solutions to geometric evolution equations has been to use a surgery procedure. This idea was first used by Hamilton [6] to avoid the development of singularities in Ricci Flow.

**Definition 1.3** (Surgery, [8]). A mean curvature flow with surgery consists of the following data:

1) An initial smooth hypersurface $\Sigma \subset \mathbb{R}^{n+1}$.
2) Constants $\omega_1 < \omega_2 < 1$ and $H > 0$.
3) A finite collection of times $0 < t_1 < t_2 \ldots < t_m$ called surgery times (let $t_0 = 0$).
4) A collection of mean curvature flows $\Sigma_i^t$ on $[t_i, t_{i+1}]$, with $\Sigma_0^0 = \Sigma$, such that for each $i$ the maximum mean curvature on $\Sigma_i^t$ is $H$ and is achieved only when $t = t_{i+1}$.
5) A surgery algorithm that consists of two steps:
   i) At each surgery time a finite number of necks with mean curvature greater than $\omega_1 H$ are removed from $\Sigma_i^{t_{i+1}}$ and replaced with convex caps with mean curvature bounded by $\omega_2 H$. The operation of replacing a single neck with two convex caps is called a standard surgery.
   ii) Finitely many components of the hypersurface constructed in i) are removed. These components are recognized as being diffeomorphic to either $S^{n-1} \times S^1$ or $S^n$.

The result of the surgery algorithm is a smooth hypersurface $\Sigma_{i+1}^{t_{i+1}}$ with mean curvature bounded by $\omega_2 H$.

We denote by $\Sigma_H \subset \mathbb{R}^{n+2}$ the space-time track swept-out by the hypersurfaces, and say that $\Sigma_H$ is a mean curvature flow with surgery performed with parameter $H$.

The main result of [8] is that a mean curvature flow with surgery can be constructed when the initial data is a closed two-convex hypersurface of dimension at least three. A hypersurface $\Sigma \subset \mathbb{R}^{n+1}$ is two-convex if the sum of the two smallest principal curvatures is everywhere nonnegative. It is proved that for any such initial data there exist $\omega_1$, $\omega_2$ and $H_0 > 0$ so that the surgery may be performed with any parameter $H \geq H_0$. In particular, $\omega_1$ and $\omega_2$ can be fixed independently of $H$. It is also shown that if the initial data is embedded then the hypersurface remains embedded even after a surgery time.

It will be convenient to work with the regions bounded by the evolving hypersurface. Let $K \subset \mathbb{R}^{n+1}$ be a compact domain such that $\partial K$ is a smooth two-convex hypersurface. Then if $\partial K_H$ is a mean curvature flow with surgery we define $K_H \subset \mathbb{R}^{n+2}$ to be the region of space-time such that the $t = T$ time-slice of $\hat{K}_H$ is the compact domain bounded by $(\partial K_H)_T$. 
The hypersurface \((\partial K_H)_t\) may not be connected after the first surgery time. However, the domains bounded by the connected components of \((\partial K_H)_t\) will be disjoint so that \((K_H)_t\) is well-defined. Thus \(K_H\) is an evolution of a union of domains whose boundary is a mean curvature flow with surgery performed with parameter \(H\) in the sense defined above. We will also refer to \(K_H\) as a mean curvature flow with surgery.

If \(K\) is a compact domain and \(K_H\) is a mean curvature flow with surgery constructed as in \([8]\) then it is easy to verify that \(K_H\) is a weak set flow for \(K\). Note that this is not true if we consider only the evolving hypersurfaces i.e., \(\partial K_H\) is not a weak set flow of \(\partial K\).

**Notation 1.4.** If \(K_H\) is a mean curvature flow with surgery, and \(T\) is a surgery time, then we use \((\partial K_H)^-\) and \((\partial K_H)^+\) to refer to the pre- and post-surgery hypersurfaces at time \(T\), and \((K_H)^-\) and \((K_H)^+\) to refer to the regions they bound.

## 2. Convergence

In this section we prove the convergence to level set flow. Recall that \(\hat{K}\) denotes the space-time track of the level set flow of \(K\).

**Theorem A.** Let \(K \subset \mathbb{R}^{n+1}, n \geq 3\), be a compact domain with \(\partial K\) a smooth embedded two-convex hypersurface. For \(H\) sufficiently large let \(K_H \subset \mathbb{R}^{n+2}\) be the result of the Huisken-Sinestrari surgery performed with parameter \(H\), and initial condition \((K_H)_0 = K\). Then

\[
\lim_{H \to \infty} K_H = \hat{K}.
\]

**Remark 2.1.** Convergence is with respect to the Hausdorff topology on closed sets of \(\mathbb{R}^{n+2}\).

Theorem A follows from the following lemma regarding the surgery procedure, and a barrier argument. As usual, \(B_\epsilon(x) \subset \mathbb{R}^{n+1}\) represents the ball of radius \(\epsilon\) centered at \(x\).

**Lemma 2.2.** Given \(\epsilon > 0\) there exists \(H_0 > 0\) such that if \(H \geq H_0\), \(T\) is a surgery time, and \(x \in \mathbb{R}^{n+1}\), then

\[
B_\epsilon(x) \subset (K_H)^- \implies B_\epsilon(x) \subset (K_H)^+.\]

The proof of Lemma 2.2 requires geometric information regarding the necks along which a surgery is performed. The parameter \(H\) here corresponds to \(H_3\) in \([8]\), and \(\omega_1, \omega_2\) are the constants appearing in Definition 2.3. Define \(H_1 = \omega_1 H\) and \(H_2 = \omega_2 H\). Furthermore, \(\epsilon_0, k, \Lambda\) are constant defined in \([8]\) and depend only on the initial hypersurface.

**Proof of Lemma 2.2.** Let \(K_H\) be a mean curvature flow with surgery.

Since \(T\) is a surgery time the Huisken-Sinestrari algorithm identifies a finite collection of subsets, \(\{A_i\}_{i=1}^m\), which cover the regions of \((\partial K_H)^-\) with mean curvature greater than \(H_2\). There are three possibilities for the structure of each \(A_i\) depending on whether it has 0,1 or 2 boundary components.

If \(\partial A_i \neq \emptyset\) then for each component of \(\partial A_i\) a standard surgery is performed. According to \([8]\) there exists an embedding \(N : S^{n-1} \times [a,b] \to A_i\) with strong geometric properties.
In particular, each $\Sigma_z = N(S^{n-1} \times z)$ has constant mean curvature $\frac{n-1}{r_z}$, where $r_z$ is called the mean radius of $\Sigma_z$. If $\partial A_i$ consists of two connected components then the map $N$ is a diffeomorphism. In general, $\partial A_i$ contains at least one of $\Sigma_a$ or $\Sigma_b$ and the mean curvature on $\partial A_i$ is $\frac{H_i}{r_z}$. 

Suppose $\Sigma_a \subset \partial A_i$. We consider the standard surgery corresponding to $\Sigma_a$. Let $z_0 \in [a, b]$ be the point closest to $a$ such that the mean curvature on $\Sigma_{z_0}$ is $H_{1}$. The slice $\Sigma_{z_0}$ is sufficiently far from $\partial A_i$ in the sense that $a < z_0 - 4\Lambda < z_0 + 4\Lambda < b$, where $\Lambda \geq 10$. For simplicity we will assume that $z_0 = 0$. The map $N$ can be extended (after first restricting it to $S^{n-1} \times [-4\Lambda, 4\Lambda]$) to a local diffeomorphism

$$G : B^n_1 \times [-4\Lambda, 4\Lambda] \to \mathbb{R}^{n+1}$$

which is $\varepsilon_0$-close in the $C^{k+1}$-norm to the standard isometric embedding of some tube $B^n \times [-4\Lambda, 4\Lambda]$ in $\mathbb{R}^{n+1}$ [8, Prop. 3.25]. The standard surgery removes $N(S^{n-1} \times [-3\Lambda, 3\Lambda])$ and replaces it by two convex caps contained in $G(B^n_1 \times [-3\Lambda, 3\Lambda])$, and the result is again a smooth embedded hypersurface [8, Thm. 3.26]. By the Jordan-Brouwer Separation Theorem for hypersurfaces it follows that if $x \in (K_H)_T \setminus G(B^n_1 \times [-3\Lambda, 3\Lambda])$ then $x$ will remain in the interior of the hypersurface after the standard surgery.

Since $G$ is $\varepsilon_0$-close to a standard tube and $\Lambda \geq 10$ is sufficiently large compared to $\varepsilon_0$ we can choose $H_0$ large enough (and hence the radius of the tube small enough) so that if $H \geq H_0$ then

$$B_\varepsilon(x) \subset (K_H)_T \implies B_\varepsilon(x) \cap G(B^n_1 \times [-3\Lambda, 3\Lambda]) = \emptyset.$$ 

With $H_0$ chosen in this way it follows that if $B_\varepsilon(x) \subset (K_H)_T$ then $B_\varepsilon(x)$ lies in the region bounded by the hypersurface after a standard surgery. At each surgery time a finite number of standard surgeries may be performed. However, the solid tubes associated to the surgeries are disjoint and so the surgeries do not interact.

It remains to verify that components discarded by 5)ii) of Definition 2.3 do not bound a ball of radius $\varepsilon$. There are three ways in which such a component can arise:

1) If $\partial A_i = \emptyset$ then $A_i$ is diffeomorphic to $S^n$ or $S^{n-1} \times S^1$ and is discarded.

2) If $\partial A_i$ consists of a single component then $A_i$ is homeomorphic to a ball. This corresponds to the case where the curvature does not decrease significantly in one direction along the neck. In this case only one standard surgery is performed. After the standard surgery, the end of the cylinder with high curvature will have become diffeomorphic to $S^n$ and will be discarded.

3) If $\partial A_i$ consists of two components then a standard surgery is performed for each boundary component and the result is two capped cylinders and a component diffeomorphic to $S^2$. The $S^2$ component is discarded.

In each case the construction in [8] guarantees that the mean curvature of the component being removed is bounded from below by $\frac{H_i}{r_z}$. Suppose $\Sigma$ is such a hypersurface, that $x$ lies in the region bounded by $\Sigma$ and that $d = d(x, \Sigma) \geq \varepsilon$. If $y \in \Sigma$ realizes $d(x, \Sigma)$ then the mean curvature at $y$ is not more than $\frac{4}{d} \leq \frac{4}{\varepsilon}$ since $\Sigma \cap \text{int}(B_d(x)) = \emptyset$. This is a contradiction as long as $H_0 \geq \frac{2n}{\varepsilon \omega_1}$. \[\square\]
**Proof of Theorem A.** Given $\epsilon > 0$ sufficiently small let $t_\epsilon > 0$ be the time such that
$$d(\partial K, \partial K_{t_\epsilon}) = \epsilon.$$ Such a time exists since $\partial K$ is two-convex. Let $\Omega_{t_\epsilon} \subset \mathbb{R}^{n+2}$ be the level set flow $K_{t_\epsilon}$. Then $\Omega_{t_\epsilon}$ is the level set flow of $K$ shifted backwards in time by $t_\epsilon$ (ignoring $t < 0$).

Let $H_0 = H_0(\epsilon)$ be chosen as in Lemma 2.2.

Claim: $\Omega_{t_\epsilon} \subset K_H$ for all $H \geq H_0$.

Let $T$ be the first surgery time of $K_H$. Since $\partial K_H$ is a smooth mean curvature flow on $[0, T)$ and $\Omega_{t_\epsilon}$ is a weak set flow the distance between the two is nondecreasing on that interval. Thus $d((\Omega_{t_\epsilon})_T, (\partial K_H)_T) \geq \epsilon$ since $t_\epsilon$ was chosen so that $d((\Omega_{t_\epsilon})_0, (\partial K_H)_0) = \epsilon$.

Applying Lemma 2.2 we conclude that $d((\Omega_{t_\epsilon})_T, (\partial K_H)_T) \geq \epsilon$. Since $(\partial K_H)_T$ is a smooth hypersurface the argument can be repeated for each of the subsequent surgery times. This proves the claim.

Since $\lim_{\epsilon \to 0} \Omega_{t_\epsilon} = \hat{K}$ the claim implies that $\hat{K} \subset \lim_{H \to \infty} K_H$ since the limit of closed sets is closed. Finally, since each mean curvature flow with surgery is a weak set flow for $K$ the limit is also and thus $\lim_{H \to \infty} K_H \subset \hat{K}$. \[\square\]

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