

VOLUME PRESERVING EMBEDDINGS OF OPEN SUBSETS OF \mathbb{R}^n INTO MANIFOLDS

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ABSTRACT. We consider a connected smooth n -dimensional manifold M endowed with a volume form Ω , and we show that an open subset U of \mathbb{R}^n of Lebesgue measure $\text{Vol}(U)$ embeds into M by a smooth volume preserving embedding whenever the volume condition $\text{Vol}(U) \leq \text{Vol}(M, \Omega)$ is met.

1. INTRODUCTION

Consider a connected smooth n -dimensional manifold M with or without boundary. A volume form on M is a smooth nowhere vanishing differential n -form Ω . It follows that M is orientable. We orient M such that $\int_M \Omega$ is positive, and we write $\text{Vol}(M, \Omega) = \int_M \Omega$. We endow each open (not necessarily connected) subset U of \mathbb{R}^n with the Euclidean volume form

$$\Omega_0 = dx_1 \wedge \cdots \wedge dx_n.$$

A smooth embedding $\varphi: U \hookrightarrow M$ is called volume preserving if

$$\varphi^* \Omega = \Omega_0.$$

Then $\text{Vol}(U, \Omega_0) \leq \text{Vol}(M, \Omega)$. In this note we prove that this obvious condition for the existence of a volume preserving embedding is the only one.

Theorem 1. *Consider an open subset U of \mathbb{R}^n and a smooth connected n -dimensional manifold M endowed with a volume form Ω . Then there exists a volume preserving embedding $\varphi: U \hookrightarrow M$ if and only if $\text{Vol}(U, \Omega_0) \leq \text{Vol}(M, \Omega)$.*

If U is a bounded subset whose boundary has zero measure and if $\text{Vol}(U, \Omega_0) < \text{Vol}(M, \Omega)$, Theorem 1 is an easy consequence of Moser's deformation method. Moreover, if U is a ball and M is compact, Theorem 1 has been proved in [K]. The main point of this note therefore is to show that Theorem 1 holds true for an arbitrary open subset of \mathbb{R}^n and an arbitrary connected manifold even in the case that the volumes are equal.

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2. PROOF OF THEOREM 1

Assume first that $\varphi: U \hookrightarrow M$ is a smooth embedding such that $\varphi^*\Omega = \Omega_0$. Then

$$\text{Vol}(U, \Omega_0) = \int_U \Omega_0 = \int_U \varphi^*\Omega = \int_{\varphi(U)} \Omega \leq \int_M \Omega = \text{Vol}(M, \Omega).$$

Assume now that $\text{Vol}(U, \Omega_0) \leq \text{Vol}(M, \Omega)$. We are going to construct a smooth embedding $\varphi: U \hookrightarrow M$ such that $\varphi^*\Omega = \Omega_0$.

We orient \mathbb{R}^n in the natural way. The orientations of \mathbb{R}^n and M orient each open subset of \mathbb{R}^n and M . We abbreviate the Lebesgue measure $\text{Vol}(V, \Omega_0)$ of a measurable subset V of \mathbb{R}^n by $|V|$, and we write \overline{V} for the closure of V in \mathbb{R}^n . Moreover, we denote by B_r the open ball in \mathbb{R}^n of radius r centered at the origin.

Proposition 2. *Assume that V is a non-empty open subset of \mathbb{R}^n . Then there exists a smooth embedding $\sigma: V \hookrightarrow \mathbb{R}^n$ such that $|\mathbb{R}^n \setminus \sigma(V)| = 0$.*

Proof. We choose an increasing sequence

$$V_1 \subset V_2 \subset \cdots \subset V_k \subset V_{k+1} \subset \cdots$$

of non-empty open subsets of V such that $\overline{V_k} \subset V_{k+1}$, $k = 1, 2, \dots$, and $\bigcup_{k=1}^{\infty} V_k = V$. To fix the ideas, we assume that the sets V_k have smooth boundaries.

Let $\sigma_1: V_1 \hookrightarrow \mathbb{R}^n$ be a smooth embedding such that $\sigma_1(V_1) \subset B_1$ and

$$|B_1 \setminus \sigma_1(V_1)| \leq 2^{-1}.$$

Since $\overline{V_1} \subset V_2$ and $\overline{\sigma_1(V_1)} \subset \overline{B_1} \subset B_2$, we find a smooth embedding $\sigma_2: V_2 \hookrightarrow \mathbb{R}^n$ such that $\sigma_2|_{V_1} = \sigma_1|_{V_1}$ and $\sigma_2(V_2) \subset B_2$ and

$$|B_2 \setminus \sigma_2(V_2)| \leq 2^{-2}.$$

Arguing by induction we find smooth embeddings $\sigma_k: V_{k+1} \hookrightarrow \mathbb{R}^n$ such that $\sigma_k|_{V_{k-1}} = \sigma_{k-1}|_{V_{k-1}}$ and $\sigma_k(V_k) \subset B_k$ and

$$(1) \quad |B_k \setminus \sigma_k(V_k)| \leq 2^{-k},$$

$k = 1, 2, \dots$. The map $\sigma: V \rightarrow \mathbb{R}^n$ defined by $\sigma|_{V_k} = \sigma_k|_{V_k}$ is a well defined smooth embedding of V into \mathbb{R}^n . Moreover, the inclusions $\sigma_k(V_k) \subset \sigma(V)$ and the estimates (1) imply that

$$|B_k \setminus \sigma(V)| \leq |B_k \setminus \sigma_k(V_k)| \leq 2^{-k},$$

and so

$$|\mathbb{R}^n \setminus \sigma(V)| = \lim_{k \rightarrow \infty} |B_k \setminus \sigma(V)| = 0.$$

This completes the proof of Proposition 2. \square

Our next goal is to construct a smooth embedding of \mathbb{R}^n into the connected n -dimensional manifold M such that the complement of the image has measure zero. If M is compact, such an embedding has been obtained by Ozols [O] and Katok [K, Proposition 1.3]. While Ozols combines an engulfing method with tools from Riemannian geometry, Katok successively exhausts a smooth triangulation of M . Both approaches can be generalized to the case of an arbitrary connected manifold M , and we shall follow Ozols.

We abbreviate $\mathbb{R}_{>0} = \{r \in \mathbb{R} \mid r > 0\}$ and $\overline{\mathbb{R}}_{>0} = \mathbb{R}_{>0} \cup \{\infty\}$. We endow $\overline{\mathbb{R}}_{>0}$ with the topology whose base of open sets consists of the intervals $]a, b[\subset \mathbb{R}_{>0}$ and the subsets of the form $]a, \infty[=]a, \infty[\cup \{\infty\}$. We denote the Euclidean norm on \mathbb{R}^n by $\|\cdot\|$ and the unit sphere in \mathbb{R}^n by S_1 .

Proposition 3. *Endow \mathbb{R}^n with its standard smooth structure, let $\mu: S_1 \rightarrow \overline{\mathbb{R}}_{>0}$ be a continuous function and let*

$$S = \left\{ x \in \mathbb{R}^n \mid 0 \leq \|x\| < \mu\left(\frac{x}{\|x\|}\right) \right\}$$

be the starlike domain associated with μ . Then S is diffeomorphic to \mathbb{R}^n .

Remark 4. The diffeomorphism guaranteed by Proposition 3 may be chosen such that the rays emanating from the origin are preserved.

Proof of Proposition 3. If $\mu(S_1) = \{\infty\}$, there is nothing to prove. In the case that μ is bounded, Proposition 3 has been proved by Ozols [O]. In the case that neither $\mu(S_1) = \{\infty\}$ nor μ is bounded, Ozols's proof readily extends to this situation. Using his notation, the only modifications needed are: Require in addition that $r_0 < 1$ and that $\epsilon_1 < 2$, and define continuous functions $\tilde{\mu}_i: S_1 \rightarrow \mathbb{R}_{>0}$ by

$$\tilde{\mu}_i = \min \left\{ i, \mu - \epsilon_i + \frac{\delta_i}{2} \right\}.$$

With these minor adaptations the proof in [O] applies word-by-word. \square

In the following we shall use some basic Riemannian geometry. We refer to [KN] for basic notions and results in Riemannian geometry. Consider an n -dimensional complete Riemannian manifold (N, g) . We denote the cut locus of a point $p \in N$ by $C(p)$.

Corollary 5. *The maximal normal neighbourhood $N \setminus C(p)$ of any point p in an n -dimensional complete Riemannian manifold (N, g) is diffeomorphic to \mathbb{R}^n endowed with its standard smooth structure.*

Proof. Fix $p \in N$. We identify the tangent space $(T_p N, g(p))$ with Euclidean space \mathbb{R}^n by a (linear) isometry. Let $\exp_p: \mathbb{R}^n \rightarrow N$ be the exponential map at p with respect to g , and let S_1 be the unit sphere in \mathbb{R}^n . We define the function $\mu: S_1 \rightarrow \overline{\mathbb{R}}_{>0}$ by

$$(2) \quad \mu(x) = \inf \{ t > 0 \mid \exp_p(tx) \in C(p) \}.$$

Since the Riemannian metric g is complete, the function μ is continuous [KN, VIII, Theorem 7.3]. Let $S \subset \mathbb{R}^n$ be the starlike domain associated with μ . In view of Proposition 3 the set S is diffeomorphic to \mathbb{R}^n , and in view of [KN, VIII, Theorem 7.4 (3)] we have $\exp_p(S) = N \setminus C(p)$. Therefore, $N \setminus C(p)$ is diffeomorphic to \mathbb{R}^n . \square

A main ingredient of our proof of Theorem 1 are the following two special cases of a theorem of Greene and Shiohama [GS].

Proposition 6. (i) *Assume that Ω_1 is a volume form on the connected open subset U of \mathbb{R}^n such that $\text{Vol}(U, \Omega_1) = |U| < \infty$. Then there exists a diffeomorphism ψ of U such that $\psi^* \Omega_1 = \Omega_0$.*

(ii) *Assume that Ω_1 is a volume form on \mathbb{R}^n such that $\text{Vol}(\mathbb{R}^n, \Omega_1) = \infty$. Then there exists a diffeomorphism ψ of \mathbb{R}^n such that $\psi^* \Omega_1 = \Omega_0$.*

End of the proof of Theorem 1. Let $U \subset \mathbb{R}^n$ and (M, Ω) be as in Theorem 1. After enlarging U , if necessary, we can assume that $|U| = \text{Vol}(M, \Omega)$. We set $N = M \setminus \partial M$. Then

$$(3) \quad |U| = \text{Vol}(M, \Omega) = \text{Vol}(N, \Omega).$$

Since N is a connected manifold without boundary, there exists a complete Riemannian metric g on N . Indeed, according to a theorem of Whitney [W], N can be embedded as a closed submanifold in some \mathbb{R}^m . We can then take the induced Riemannian metric. A direct and elementary proof of the existence of a complete Riemannian metric is given in [NO].

Fix a point $p \in N$. As in the proof of Corollary 5 we identify $(T_p N, g(p))$ with \mathbb{R}^n and define the function $\mu: S_1 \rightarrow \overline{\mathbb{R}}_{>0}$ as in (2). Using polar coordinates on \mathbb{R}^n we see from Fubini's Theorem that the set

$$\tilde{C}(p) = \{\mu(x)x \mid x \in S_1\} \subset \mathbb{R}^n$$

has measure zero, and so $C(p) = \exp_p(\tilde{C}(p))$ also has measure zero (see [Bo, VI, Corollary 1.14]). It follows that

$$(4) \quad \text{Vol}(N \setminus C(p), \Omega) = \text{Vol}(N, \Omega).$$

According to Corollary 5 there exists a diffeomorphism

$$\delta: \mathbb{R}^n \rightarrow N \setminus C(p).$$

After composing δ with a reflection of \mathbb{R}^n , if necessary, we can assume that δ is orientation preserving. In view of (3) and (4) we then have

$$(5) \quad |U| = \text{Vol}(\mathbb{R}^n, \delta^* \Omega).$$

Case 1. $|U| < \infty$.

Let $U_i, i = 1, 2, \dots$, be the countably many components of U . Then $0 < |U_i| < \infty$ for each i . Given numbers a and b with $-\infty \leq a < b \leq \infty$ we abbreviate the “open strip”

$$S_{a,b} = \{(x_1, \dots, x_n) \in \mathbb{R}^n \mid a < x_1 < b\}.$$

In view of the identity (5) we have

$$\sum_{i \geq 1} |U_i| = |U| = \text{Vol}(\mathbb{R}^n, \delta^* \Omega).$$

We can therefore inductively define $a_0 = -\infty$ and $a_i \in]-\infty, \infty]$ by

$$\text{Vol}(S_{a_{i-1}, a_i}, \delta^* \Omega) = |U_i|.$$

Abbreviating $S_i = S_{a_{i-1}, a_i}$ we then have $\mathbb{R}^n = \bigcup_{i \geq 1} \overline{S_i}$.

For each $i \geq 1$ we choose an orientation preserving diffeomorphism $\tau_i: \mathbb{R}^n \rightarrow S_i$. In view of Proposition 2 we find a smooth embedding $\sigma_i: U_i \hookrightarrow \mathbb{R}^n$ such that $\mathbb{R}^n \setminus \sigma_i(U_i)$ has measure zero. After composing σ_i with a reflection of \mathbb{R}^n , if necessary, we can assume that σ_i is orientation preserving. Using the definition of the volume, we can now conclude that

$$\text{Vol}(U_i, \sigma_i^* \tau_i^* \delta^* \Omega) = \text{Vol}(\sigma_i(U_i), \tau_i^* \delta^* \Omega) = \text{Vol}(\mathbb{R}^n, \tau_i^* \delta^* \Omega) = \text{Vol}(S_i, \delta^* \Omega) = |U_i|.$$

In view of Proposition 6 (i) we therefore find a diffeomorphism ψ_i of U_i such that

$$(6) \quad \psi_i^* (\sigma_i^* \tau_i^* \delta^* \Omega) = \Omega_0.$$

We define $\varphi_i: U_i \hookrightarrow M$ to be the composition of diffeomorphisms and smooth embeddings

$$U_i \xrightarrow{\psi_i} U_i \xrightarrow{\sigma_i} \mathbb{R}^n \xrightarrow{\tau_i} S_i \subset \mathbb{R}^n \xrightarrow{\delta} N \setminus C(p) \subset M.$$

The identity (6) implies that $\varphi_i^* \Omega = \Omega_0$. The smooth embedding

$$\varphi = \coprod \varphi_i: U = \coprod U_i \hookrightarrow M$$

therefore satisfies $\varphi^* \Omega = \Omega_0$.

Case 2. $|U| = \infty$.

In view of (5) we have $\text{Vol}(\mathbb{R}^n, \delta^* \Omega) = \infty$. Proposition 6 (ii) shows that there exists a diffeomorphism ψ of \mathbb{R}^n such that

$$(7) \quad \psi^* \delta^* \Omega = \Omega_0.$$

We define $\varphi: U \hookrightarrow M$ to be the composition of inclusions and diffeomorphisms

$$U \subset \mathbb{R}^n \xrightarrow{\psi} \mathbb{R}^n \xrightarrow{\delta} N \setminus C(p) \subset M.$$

The identity (7) implies that $\varphi^* \Omega = \Omega_0$. The proof of Theorem 1 is complete. \square

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