Alternative proof of the ribbonness on classical link

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ABSTRACT

Alternative proof is given for an earlier presented result that if a link in 3-space bounds a compact oriented proper surface (without closed component) in the upper half 4-space, then the link bounds a ribbon surface in the upper half 4-space which is a boundary-relative renewal embedding of the original surface.

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1. Introduction

For a set A in the 3-space $\mathbf{R}^3 = \{(x, y, z)| -\infty < x, y, z < +\infty\}$ and an interval $J \subset \mathbf{R}$, let

$$AJ = \{(x, y, z, t)|\,(x, y, z) \in A,\ t \in J\}.$$

The *upper-half 4-space* $\mathbf{R}^4_+$ is denoted by $\mathbf{R}^3[0, +\infty)$. Let k be a link in the 3-space $\mathbf{R}^3$, which always bounds a compact oriented proper surface F embedded smoothly in the upper-half 4-space $\mathbf{R}^4_+$, where $\mathbf{R}^3[0]$ is canonically identified with $\mathbf{R}^3$. Two such surfaces F and F' in $\mathbf{R}^4_+$ are *equivalent* if there is an orientation-preserving diffeomorphism f of $\mathbf{R}^4_+$ sending F to F', where f is called an *equivalence*. For a link k_0 in $\mathbf{R}^3$, let $\mathbf{b}$ be a band system spanning k_0, namely a system of finitely many disjoint oriented bands spanning the link k_0 in $\mathbf{R}^3$. The pair $(k_0, \mathbf{b})$ is called a *banded link*. The *surgery link* of $(k_0, \mathbf{b})$ is the link obtained from k_0 by surgery along $\mathbf{b}$. Assume that the surgery link of a banded link $(k_0, \mathbf{b})$ is a trivial link $\boldsymbol{\kappa}$ in $\mathbf{R}^3$. Then the band system $\mathbf{b}$ is considered as a band system $\boldsymbol{\beta}$ spanning $\boldsymbol{\kappa}$. The pair $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ is called a *banded loop system* with *loop system* $\boldsymbol{\kappa}$ and *surgery link* k_0. Throughout the paper, the surgery link k_0 will be a union $k \cup \mathbf{o}$ of a link k in question and a trivial link $\mathbf{o}$ called an *extra trivial link*. Here, it is assumed that there is a band sub-system $\mathbf{b}_1$ of the band system $\mathbf{b}$ such that $\mathbf{b}_1$ connects to $\mathbf{o}$ with just one band $b_1 \in \mathbf{b}_1$ for every component $o \in \mathbf{o}$ and every band $b \in \mathbf{b}_1^c = \mathbf{b} \setminus \mathbf{b}_1$ spans the link k. Let $\boldsymbol{\alpha}_1$ be the arc system of the attaching arc α_1 of every band $b_1 \in \mathbf{b}_1$ to $o \in \mathbf{o}$, and $\boldsymbol{\alpha}_1^c$ the complementary arc system of $\boldsymbol{\alpha}_1$ in $\mathbf{o}$ consisting of every complementary arc $\alpha_1^c = \mathrm{cl}(o \setminus \alpha_1)$. Any disk system $\mathbf{d}$ in $\mathbf{R}^3$ bounded by the extra trivial link $\mathbf{o}$ is called an *extra disk system*, which is fixed and the argument proceeds. Let $\boldsymbol{\delta}$ be a disk system consisting of disjoint disks in $\mathbf{R}^3$ with $\partial\boldsymbol{\delta} = \boldsymbol{\kappa}$, which is called a *based disk system* for a loop system $\boldsymbol{\kappa}$. A ribbon surface-link $\mathrm{cl}(F^1_{-1})$ in $\mathbf{R}^4$ is constructed from a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ by taking the surgery of the trivial S^2-link

$$O = \partial(\boldsymbol{\delta}[-1,1]) = \boldsymbol{\delta}[-1] \cup (\partial\boldsymbol{\delta})[-1,1] \cup \boldsymbol{\delta}[1]$$

along the 1-handle system $\boldsymbol{\beta}[-t,t]$ in $\mathbf{R}^4$ for any t with $0 < t < 1$. The proper surface $\mathrm{ucl}(F^1_0) = \mathrm{cl}(F^1_{-1}) \cap \mathbf{R}^4_+$ in $\mathbf{R}^4_+$ is called the *upper-closed realizing surface* of a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with surgery link k_0. Note that choices of the based disk systems $\boldsymbol{\delta}$ are independent of the equivalences of $\mathrm{ucl}(F^1_0)$ and $\mathrm{cl}(F^1_{-1})$ by Horibe-Yanagawa's lemma, [6]. The reason for dealing with a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ rather than a banded link $(k_0, \mathbf{b})$ is because not only can a based disk system $\boldsymbol{\delta}$ be chosen freely, but it also makes a band deformation of the band system $\boldsymbol{\beta}$ easier. Actually, an isotopic deformation of $\boldsymbol{\beta}$ respecting the arc system $\boldsymbol{\alpha}_1$ and the loop system $\boldsymbol{\kappa}$ does not change the ribbon surface-link $\mathrm{cl}(F^1_{-1})$ in $\mathbf{R}^4$ and the proper surface $\mathrm{ucl}(F^1_0)$ in $\mathbf{R}^4_+$, up to equivalences.

Let $\mathrm{cl}(F^1_{-1})_{\mathbf{d}}$ be the surface-link in $\mathbf{R}^4$ obtained from the ribbon surface-link $\mathrm{cl}(F^1_{-1})$ by surgery along the 2-handle $\mathbf{d}[-\varepsilon, \varepsilon]$ on $\mathrm{cl}(F^1_{-1})$ where $0 < \varepsilon < t < 1$. The proper surface $P(F^1_0) = \mathrm{cl}(F^1_{-1})_{\mathbf{d}} \cap \mathbf{R}^4_+$ in $\mathbf{R}^4_+$ with $\partial P(F^1_0) = k$ is called a *proper realizing surface* of a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with surgery link $k_0 = k \cup \mathbf{o}$. The following theorem is known, [6].

Normal form theorem. Every compact oriented proper surface F without closed component in the upper-half 4-space $\mathbf{R}^4_+$ with $\partial F = k$ in $\mathbf{R}^3$ is equivalent to a proper realizing surface $P(F^1_0)$ in $\mathbf{R}^4_+$ with $\partial P(F^1_0) = k$ of a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with surgery link $k_0 = k + \mathbf{o}$ which is a split sum of k and an extra trivial link $\mathbf{o}$.

The proper realizing surface $P(F_0^1)$ in $\mathbf{R}^4_+$ is called a *normal form* of the proper surface F in $\mathbf{R}^4_+$. If the extra trivial link $\mathbf{o}$ is taken the empty link, namely $P(F_0^1) = \mathrm{ucl}(F_0^1)$, then the proper surface F in $\mathbf{R}^4_+$ is called a *ribbon surface*. In the following example, it is observed that there are lots of compact oriented proper surfaces without closed component in $\mathbf{R}^4_+$ which are not equivalent to any ribbon surface in $\mathbf{R}^4_+$.

Example. For every link k in $\mathbf{R}^3$, let F' be any ribbon surface in $\mathbf{R}^4_+$ with $k = \partial F'$. For example, let F' be a proper surface in $\mathbf{R}^4_+$ obtained from a Seifert surface for k in $\mathbf{R}^3$ by an interior push into $\mathbf{R}^4_+$. Take a connected sum $F = F' \# K$ of F' and a non-trivial S^2-knot K in $\mathbf{R}^4$ with non-abelian fundamental group. Then $k = \partial F' = \partial F$. It is shown that F is not equivalent to any ribbon surface in $\mathbf{R}^4_+$. The fundamental groups of k, F', F, K are denoted as follows.

$$\pi(k) = \pi_1(\mathbf{R}^3 \setminus k, x_0), \quad \pi(F') = \pi_1(\mathbf{R}^4 \setminus F', x_0),$$

$$\pi(F) = \pi_1(\mathbf{R}^4 \setminus F, x_0), \quad \pi(K) = \pi_1(S^4 \setminus K, x_0).$$

Let $\pi(k)^*, \pi(F')^* \pi(F)^*, \pi(K)^*$ be the kernels of the canonical epimorphisms from the groups $\pi(k), \pi(F'), \pi(F), \pi(K)$ to the infinite cyclic group sending every meridian element to the generator, respectively. It is a special feature of a ribbon surface F' that the canonical homomorphism $\pi(k) \to \pi(F')$ is an epimorphism, so that the induced homomorphism $\pi(k)^* \to \pi(F')^*$ is onto. On the other hand, the canonical homomorphism $\pi(k) \to \pi(F)$ is not onto, because the group $\pi(F)^*$ is the free product $\pi(F')^* * \pi(K)^*$ and $\pi(K)^* \neq 0$ and the image of the induced homomorphism $\pi(k)^* \to \pi(F)^*$ is just the free product summand $\pi(F')^*$. Thus, the proper surface F in $\mathbf{R}^4_+$ is not equivalent to any ribbon surface.

A compact oriented proper surface F' in $\mathbf{R}^4_+$ is a *renewal embedding* of a compact oriented proper surface F in $\mathbf{R}^4_+$ if there is an orientation-preserving surface-diffeomorphism $F' \to F$ keeping the boundary fixed. A renewal embedding F' of F is *boundary-relative* if the link $k' = \partial F'$ in $\mathbf{R}^3$ is equivalent to the link $k = \partial F$ in $\mathbf{R}^3$. The proof of the following theorem is given, [4]. In this paper, an alternative proof of this theorem is given from a viewpoint of deformations of a ribbon surface-link in $\mathbf{R}^4$.

Classical ribbon theorem. Assume that a link k in the 3-space $\mathbf{R}^3$ bounds a compact oriented proper surface F without closed component in the upper-half 4-space $\mathbf{R}^4_+$. Then the link k in $\mathbf{R}^3$ bounds a ribbon surface F' in $\mathbf{R}^4_+$ which is a boundary-relative renewal embedding of F.

A link k in $\mathbf{R}^3$ is a *slice link in the strong sense* if k bounds a proper disk system embedded smoothly in $\mathbf{R}^4_+$. A link k in $\mathbf{R}^3$ is a *ribbon link* if k bounds a ribbon disk system in $\mathbf{R}^4_+$. The following corollary is a special case of Classical ribbon theorem.

Corollary 1. Every slice link in the strong sense in $\mathbf{R}^3$ is a ribbon link.

Thus, Classical ribbon theorem solves *Slice-Ribbon Problem*, [1], [2]. The following corollary is obtained from Corollary 1.

Corollary 2. A link k in $\mathbf{R}^3$ is a ribbon link if a ribbon link is obtained from the split sum $k + \mathbf{o}$ of k and a trivial link $\mathbf{o}$ by a band sum of k and every component of $\mathbf{o}$.

The proof of the classical ribbon theorem is done throughout the section 2. An idea of the proof is to consider the 2-handle pair system $(D \times I, D' \times I)$ on the ribbon surface-link $\mathrm{cl}(F^1_{-1})$ with $k + \mathbf{o}$ as the middle-cross sectional link such that $P(F^1_0)$ is equivalent to a previously given surface F in $\mathbf{R}^4_+$, where the 2-handle system $D \times I$ is constructed from the band system $\mathbf{b}_1$ and the 2-handle system $D' \times I$ is constructed from the extra disk system $\mathbf{d}$. The interior intersections of $(D \times I, D' \times I)$ will be eliminated and $(D \times I, D' \times I)$ becomes an O2-handle pair system on a new ribbon surface-link $\mathrm{cl}(F^1_{-1})$ with $k + \mathbf{o}$ as the middle-cross sectional link obtained by sacrificing equivalences. Then $P(F^1_0)$ is a ribbon surface that is a boundary-relative renewal embedding of F, which will complete the proof.

2. Proof of Classical ribbon theorem

Throughout this section, the proof of the classical ribbon theorem is done. Let F be a compact oriented proper surface without closed component in $\mathbf{R}^4_+$, and $\partial F = k$ a link in $\mathbf{R}^3$. By the normal form theorem, there is a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with surgery link $k_0 = k + \mathbf{o}$ such that $P(F^1_0)$ is equivalent to F. The extra trivial link $\mathbf{o}$ is uniquely specified by the banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$, which is the union of the arc system $\boldsymbol{\alpha}_1$ and the complementary arc system $\boldsymbol{\alpha}^c_1$, where the interior of $\boldsymbol{\alpha}_1$ transversely meets the interior of a based disk system $\boldsymbol{\delta}$ with finite points and is disjoint from the based loop system $\boldsymbol{\kappa}$ and $\boldsymbol{\alpha}^c_1$ belongs to the loop system $\boldsymbol{\kappa}$.

A *renewal embedding* of a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with surgery link $k_0 = k \cup \mathbf{o}$ is a banded loop system $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ with surgery link $k'_0 = k' \cup \mathbf{o}$ such that there is a homeomorphism $\boldsymbol{\kappa} \cup \boldsymbol{\beta} \to \boldsymbol{\kappa}' \cup \boldsymbol{\beta}'$ with restrictios $\boldsymbol{\kappa} \to \boldsymbol{\kappa}'$ and $\boldsymbol{\beta} \to \boldsymbol{\beta}'$ orientation-preserved.

The following observation is directly obtained by definition.

(2.1) If a banded loop system $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ with surgery link $k' \cup \mathbf{o}$ is a renewal embedding of a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with surgery link $k \cup \mathbf{o}$, then the upper-closed realizing surface $\mathrm{ucl}(F_0^1)'$ constructed from $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ is a renewal embedding of the upper-closed realizing surface $\mathrm{ucl}(F_0^1)$ constructed from $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ such that $\partial \mathrm{ucl}(F_0^1) = k \cup \mathbf{o}$ and $\partial \mathrm{ucl}(F_0^1)' = k' \cup \mathbf{o}$.

A *transversal arc* of a band spanning a link is a simple proper arc in the band which is parallel to an attaching arc. For a band $b \in \mathbf{b}$ transversely meeting the interior of an extra disk $d \in \mathbf{d}$, the *d-arc system* of b is the arc system $d(b)$ of every transversal arc a of b in the interior of d. The $\mathbf{d}$-arc system of a band system $\mathbf{b}$ is the collection $\mathbf{d}(\mathbf{b})$ of $d(b)$ for every $d \in \mathbf{d}$ and every $b \in \mathbf{b}$. For a based disk $\delta \in \boldsymbol{\delta}$, the *$\delta$-arc system* of a band $\beta \in \boldsymbol{\beta}$ is the arc system $\delta(\beta)$ of every transversal arc c of β in the interior of δ. The $\boldsymbol{\delta}$-arc system of $\boldsymbol{\beta}$ is the collection $\boldsymbol{\delta}(\boldsymbol{\beta})$ of $\delta(\beta)$ for every $\delta \in \boldsymbol{\delta}$ and every $\beta \in \boldsymbol{\beta}$. A *normal proper arc* in the extra disk system $\mathbf{d}$ is a simple proper arc in $\mathbf{d}$ with the endpoints in the interior of the arc system $\boldsymbol{\alpha}_1$. The following assertion is shown.

(2.2) By isotopic deformations in $\mathbf{R}^3$, the banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ in $\mathbf{R}^3$ with surgery link $k_0 = k + \mathbf{o}$ is deformed so that a based disk system $\boldsymbol{\delta}$ transversely meets the extra disk system $\mathbf{d}$ with interior simple arcs or normal proper arcs in $\mathbf{d}$ except for the complementary arc system $\boldsymbol{\alpha}_1^c$.

Proof of (2.2). By transverse regularity, the intersection $d \cap \delta$ for every $d \in \mathbf{d}$ and every $\delta \in \boldsymbol{\delta}$ is made interior simple loops, interior simple arcs, clasp type simple arcs or simple proper arcs in $\mathbf{d}$ except for the complementary arc system $\boldsymbol{\alpha}_1^c$. A simple loop is changed into a normal proper arc by a pushing out deformation to $\boldsymbol{\alpha}_1$, Fig. 1 (1). A clasp type simple arc is changed into a simple proper arc by moving out the interior point to $\boldsymbol{\alpha}_1$, Fig. 1 (2). A simple proper arc which is not normal is also changed into a normal proper arc by a pushing out deformation of the arc system of $\boldsymbol{\delta}$ meeting a boundary collar of $\boldsymbol{\alpha}_1^c$ in $\mathbf{d}$, Fig. 1 (3). Thus, a deformed based disk system $\boldsymbol{\delta}$ transversely meets $\mathbf{d}$ with interior simple arcs or normal proper arcs in $\mathbf{d}$ except for the complementary arc system $\boldsymbol{\alpha}_1^c$. This completes the proof of (2.2).

The following operation gives a standard renewal embedding of a banded loop system.

Band Move Operation. In the banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with surgery link $k_0 =$

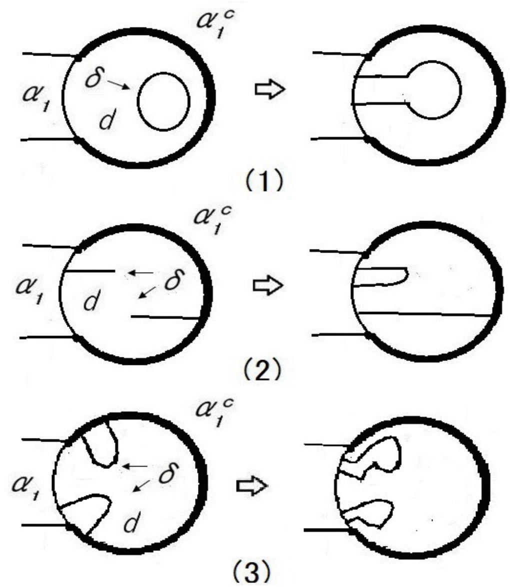

Figure 1: Changing the intersection of a based disk and an extra disk

$k \cup \mathbf{o}$, assume that there is a transversal arc c of a band $\beta \in \boldsymbol{\beta}$ in the interior of an extra disk $d \in \mathbf{d}$ and there is a simple path ω in d from a point $p \in c$ to an interior point of the arc $\alpha_1^c = \partial d \cap \boldsymbol{\alpha}_1^c$ which avoids meeting $\boldsymbol{\beta}$ other than c. Let β' be a band obtained from β by sliding the arc c off the disk d along the path ω. Replace the banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with the banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta}')$ obtained by replacing β with β', Fig. 2.

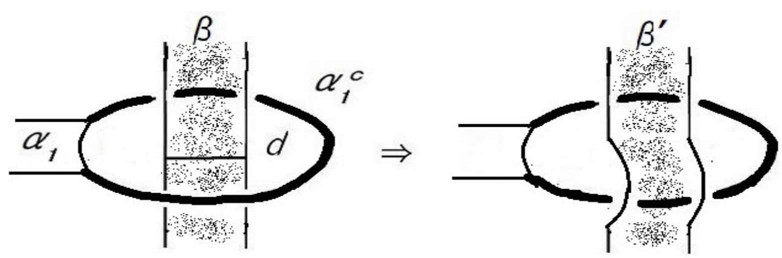

Figure 2: Band Move Operation

By this operation, the new banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta}')$ is a renewal embedding of the original banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ and has as the surgery link a new union k_0' of the same links k and $\mathbf{o}$, not necessarily the split sum $k + \mathbf{o}$, because the band system $\boldsymbol{\beta}'$ is isotopic to $\boldsymbol{\beta}$ if $\boldsymbol{\alpha}_1^c$ is forgotten. In the final stage of this paper, the surgery link k_0' will have $k \cap \mathbf{d} = \emptyset$, so that k_0' will be the split sum $k + \mathbf{o}$, because $\mathbf{o} = \partial \mathbf{d}$.

To achieve a situation where the Band Move Operation can be applied, the follwing concept is needed. A *splitting* of a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ is a banded loop system $(\boldsymbol{\kappa}^*, \boldsymbol{\beta}^*)$ such that a based disk system $\boldsymbol{\delta}^*$ for $\boldsymbol{\kappa}^*$ is obtained from a based disk system $\boldsymbol{\delta}$ for $\boldsymbol{\kappa}$ by splitting along a disjoint proper arc system $\boldsymbol{\gamma}$ in $\boldsymbol{\delta}$ not meeting $\mathbf{o}$ and $\boldsymbol{\beta}$, and the band system $\boldsymbol{\beta}^*$ is obtained from the band system $\boldsymbol{\beta}$ by adding the band system $\boldsymbol{\beta}_{\boldsymbol{\gamma}}$ thickening $\boldsymbol{\gamma}$. This splitting operation comes from Fission-Fusion move of a banded loop system, [3]. After some splittings of a banded loop system, a situation where the Band Move Operation can be applied is realized by a replacement of the based disk system and an isotopic deformation of the band system.

The following assertion is used.

(2.3) If there is a splitting $(\boldsymbol{\kappa}^*, \boldsymbol{\beta}^*)$ of a banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with surgery knot k_0 a union of k and $\mathbf{o}$ such that $\boldsymbol{\kappa}^*$ does not meet the interior of the extra disk system $\mathbf{d}$, then there is a renewal embedding $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ of $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ such that $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ does not meet the interior of $\mathbf{d}$ and has the surgery knot $k_0' = k + \mathbf{o}$.

Proof of (2.3). Since $\boldsymbol{\kappa}^*$ does not meet the interior of $\mathbf{d}$, there is a based disk system $\boldsymbol{\delta}^*$ for $\boldsymbol{\kappa}^*$ not meeting the interior of $\mathbf{d}$. The band system $\boldsymbol{\beta}^*$ transversely meets the interior of $\mathbf{d}$ with transverse arc system A. Let $\boldsymbol{\delta}_1^*$ be the sub-system of $\boldsymbol{\delta}^*$ containing the complementary arc system $\boldsymbol{\alpha}_1^c$ in the boundary, and $N(\boldsymbol{\alpha}_1^c)$ a boundary collar disk system of $\boldsymbol{\alpha}_1^c$ in $\boldsymbol{\delta}_1^*$. The Band Move Operation means that the band system $\boldsymbol{\beta}^*$ is deformed so that the transverse arc system A moves from the interior of $\mathbf{d}$ into the interior of $N(\boldsymbol{\alpha}_1^c)$. Then by changing the band system $\boldsymbol{\beta}_{\boldsymbol{\gamma}}$ back into the arc system $\boldsymbol{\gamma}$, the banded loop system $(\boldsymbol{\kappa}^*, \boldsymbol{\beta}^*)$ is changed back to a pair $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$, where the loop system $\boldsymbol{\kappa}'$ bounds an immersed disk system $\boldsymbol{\delta}'$ obtained from the based disk system $\boldsymbol{\delta}$ by moving a transverse arc system of $\boldsymbol{\beta}_{\boldsymbol{\gamma}}$ into the interior of $N(\boldsymbol{\alpha}_1^c)$. The immersed disk system $\boldsymbol{\delta}'$ is deformed into a disjoint disk system by repeatedly pulling the band in $\boldsymbol{\beta}_{\boldsymbol{\gamma}}$ connecting to an outer most disk of $\boldsymbol{\delta}^*$ or passing the outer most disk of $\boldsymbol{\delta}^*$ through $N(\boldsymbol{\alpha}_1^c)$ in order to eliminate the nearest transverse arc of the band. This means that the loop system $\boldsymbol{\kappa}'$ is a trivial link and $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ is a banded loop system. Thus, there is a renewal embedding $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ of $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ which does not meet the interior of $\mathbf{d}$. The surgery knot k_0' is necessarily the split sum $k + \mathbf{o}$ since $\partial \mathbf{d} = \mathbf{o}$. This completes the proof of (2.3).

By using (2.2) and (2.3), the following assertion is shown.

(2.4) There is a renewal embedding $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ of every banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ in $\mathbf{R}^3$ with surgery link $k_0 = k + \mathbf{o}$ such that $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ does not meet the interior of $\mathbf{d}$ and has the surgery knot $k_0' = k + \mathbf{o}$.

Proof of (2.4). By (2.2), a based disk system $\boldsymbol{\delta}$ of $\boldsymbol{\kappa}$ transversely meets the extra disk system $\mathbf{d}$ with interior simple arcs or normal proper arcs in $\mathbf{d}$ except for the complementary arc system $\boldsymbol{\alpha}_1^c$. Let A be the interior arc system which is made disjoint from $\boldsymbol{\beta}$ by isotopic deformations of $\boldsymbol{\beta}$ respecting the arc system $\boldsymbol{\alpha}_1$ and the loop system $\boldsymbol{\kappa}$. By taking a splitting of $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ along A, it is considered that the based disk system $\boldsymbol{\delta}$ transversely meets $\mathbf{d}$ only with normal proper arcs in $\mathbf{d}$ except for $\boldsymbol{\alpha}_1^c$. Then $\boldsymbol{\kappa}$ does not meet the interior of the extra disk system $\mathbf{d}$. By (2.3), the proof of (2.4) is completed.

Let $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ be a banded loop system a banded loop system with surgery link $k_0 = k + \mathbf{o}$ such that $P(F_0^1)$ is equivalent to F. By (2.4), there is a renewal embedding $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ such that $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ does not meet the interior of the extra disk system $\mathbf{d}$, and has the surgery link $k + \mathbf{o}$. Let $\mathbf{b}'$ be the band system dual to the band system $\boldsymbol{\beta}'$, and $\mathbf{b}_1'$ the band sub-system of $\mathbf{b}'$ such that $\mathbf{b}_1'$ connects to $\mathbf{o}$ with just one band for every component of $\mathbf{o}$. Let $\mathbf{b}_2' = \mathbf{b}' \setminus \mathbf{b}_1'$. Since $\mathbf{b}_1'$ does not meet the interior of $\mathbf{d}$, the surgery link of the banded link $(k + \mathbf{o}, \mathbf{b}_1')$ is equivalent to the link k and the upper-closed realizing surface $\mathrm{ucl}(F_0^1)'$ of the banded link $(k, \mathbf{b}_2')$ is equivalent to the proper realizing surface $P(F_0^1)'$ of $(\boldsymbol{\kappa}', \boldsymbol{\beta}')$ which is a ribbon surface in $\mathbf{R}^4_+$ and is a renewal embedding of the proper realizing surface $P(F_0^1)$ of the banded loop system $(\boldsymbol{\kappa}, \boldsymbol{\beta})$ with the surgery link $k + \mathbf{o}$. Since $P(F_0^1)$ is equivalent to F in $\mathbf{R}^4_+$ and $\mathrm{ucl}(F_0^1)'$ is a ribbon surface with $\partial \mathrm{ucl}(F_0^1)' = \partial F = k$, there is a boundary-relative renewal embedding from $\mathrm{ucl}(F_0^1)'$ to F. This completes the proof of the classical ribbon theorem.

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references

[1] R. H. Fox, Some problems in knot theory, Topology of 3-manifolds and related topics, (1962), 168-176, Prentice-hall, Inc., Engelwood Cliffs, N. J. USA.

[2] R. H. Fox, Characterization of slices and ribbons, Osaka J. Math 10. (1973), 69-76.

[3] A. Kawauchi, A chord diagram of a ribbon surface-link, Journal of Knot Theory and Its Ramifications 24 (2015), 1540002 (24 pages).

[4] A. Kawauchi, Ribbonness on classical link. Journal of Mathematical Techniques and Computational Mathematics, 2 (8) (2023), 375-377, DOI:10.33140/JMTCM.

[5] A. Kawauchi, Ribbonness of a stable-ribbon surface-link, I. A stably trivial surface-link, Topology and its Applications 301(2021), 107522 (16pages).

[6] A. Kawauchi, T. Shibuya, S. Suzuki, Descriptions on surfaces in four-space I : Normal forms, Mathematics Seminar Notes, Kobe University, 10 (1982), 75-125; II: Singularities and cross-sectional links, Mathematics Seminar Notes, Kobe University 11 (1983), 31-69. Available from: https://sites.google.com/view/kawauchiwriting