A Short Proof of a Gauss Problem ⋆

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Abstract. The traversal of a self crossing closed plane curve, with points of multiplicity at most two, defines a double occurrence sequence.

C.F. Gauss conjectured [2] that such sequences could be charac-tacterized by their interlacement properties. The conjecture was by P. Rosenstiehl in 1976 [15]. We shall give here a simple self contained proof of his characterization. This new proof relies on the D-switch operation.

1 Introduction

We first recall and introduce some definitions and notations concerning geometric properties of closed plane curves. For related topics, we refer the reader to the bibliography. P. Rosenstiehl exposed recently a new proof of this theorem, based on patches, that will soon be published.

A *parameterized curve* C is a continuous mapping $C : [0,1] \to \mathbb{R}^2$, such that $C(0) = C(1)$ and such that the *underlying curve* $C([0,1])$ of C has a finite number of multiple points, which all have multiplicity two. The set of the points of multiplicity two is denoted $P(C)$. To any point $p \in P(C)$, we associate t'_p and t''_p, such that $t'_p < t''_p$ and $C(t'_p) = C(t''_p) = p$. A point $p \in P(C)$ is a *crossing point* if any local deformation of C in a neighborhood of t'_p preserves the existence of a double point. Otherwise, p is a *touching point*. A *touch curve* (resp. a *cross curve*) is a parameterized curve with touching points (resp. crossing points) only.

There are two different types of touching points, depending on the local behavior of the parameterized curve :

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Remark that if C is a touch curve, then all its touch points are of type 1.

The sequence of the points of $P(C)$ encountered while the parameter t goes from 0 to 1 (excluded) is the *traversal sequence* of C and is denoted by $S(C)$.

In the following, *sequences* are understood to have two occurrences of each symbol and to be defined up to reversal and cyclic permutation. Given a sequence S, two symbols p, q are *interlaced* in S if exactly one occurrence of q appears in S between the two occurrences of p. We shall denote by $\Lambda(S)$ the *interlacement graph* of S defined by the interlacement relation in S.

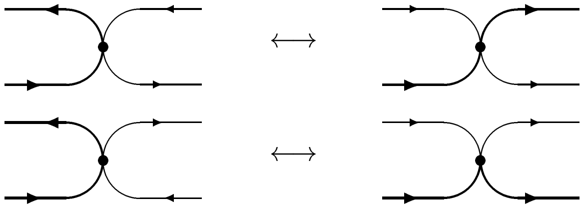
A sequence S is *realized* by a parameterized curve C if S is the traversal sequence of C. A sequence is *touch realizable* (resp. *cross realizable*) if it can be realized by a touch curve (resp. a cross curve).

2 switches and D-switches

Let us introduce the *switch* operation [4, 8] : Given a point p of $P(C)$, the curve $C' = C \circ p$ is defined by $C'(t) = C(t)$ if $t \notin [t'_p, t''_p]$ and $C'(t) = C(t'_p + t''_p - t)$ if $t \in [t'_p, t''_p]$. This curves as the same touching and crossing points as C, with the possible exception of p. The traversal sequence of C' is obtained from the one of C by inverting the order of the points encountered between the two occurrences of p. We shall say that the points that are interlaced with p have been *inverted*. The switch operation on S will be denoted by $S \circ p$, so that : $S(C \circ p) = S(C) \circ p$. Let us remark that these switch operations are involutions : $C \circ p \circ p = C$ and $S \circ p \circ p = S$.

Remark. A *switch* transforms any point of a parameterized point the following way :

- touching point of type 1 $\leftrightarrow$ crossing point,
- touching point of type 2 $\leftrightarrow$ touching point of type 2.



Remark that if q is a touching point of C different from p, then q is a touching point with a type different in C and $C \circ p$ if and only p and q are interlaced.

The switch in a sequence S of a point p induces a *local complementation* of p in the interlacement graph $\Lambda(S)$: two points a, b are adjacent in $\Lambda(S \circ p)$ if and only if

- a or b is not adjacent to p in $\Lambda(S)$ and (a, b) is an edge of $\Lambda(S)$, or
- a and b are both adjacent to p in $\Lambda(S)$ and (a, b) is not an edge of $\Lambda(S)$.

For sake of simplicity, the local complementation of p in $\Lambda(S)$ will be denoted by $\Lambda(S) \circ p$, so that $\Lambda(S \circ p) = \Lambda(S) \circ p$.

Let S be a sequence, a *D-switch* consists in a switching at p and in the adding of two occurences of a symbol p' (called *twin* of p), one just after the first occurrence of p and one just before the second occurrence of p.

$$S = (\alpha p \beta p \gamma) \mapsto S \circledcirc p = (\alpha p p' \beta^{-1} p' p \gamma)$$

A D-switch of p in S corresponds in $\Lambda(S)$ to a local complementation of p and the adding of a new vertex having the same neighbors as p. It will be denoted by the same symbol, so that $\Lambda(S) \circledcirc p = \Lambda(S \circledcirc p)$.

Remark that the sequence obtained from $S \circledcirc p \circledcirc p$ by deleting the two twins of p is equal to S.

3 On realizable sequences

We first state two propositions proved by Dehn, which follow from the remarks of the preceding sections.

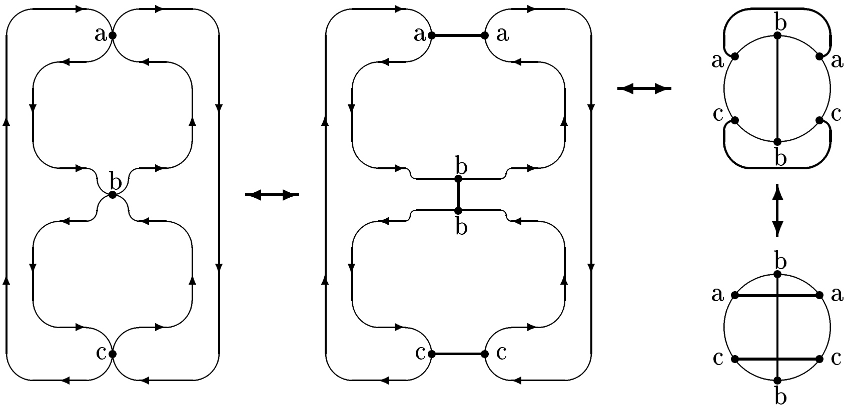
Proposition 1. *Consider a cross curve C and any given order on the points. Then, the parameterized curve $C \circ p_1 \circ \ldots \circ p_n$ obtained from C by switching successively the p_i is a touch curve.* □

Let S be a sequence and $S' = S \circ p_1 \circ \ldots \circ p_n$ the sequence obtained by switching successively the symbols of S. The sequence S' may be touch realizable even if S is not cross realizable (e.g. the sequence $S = (abab)$).

Assume S' is realized by a touch curve C and that the transformation of each touching point of C into a crossing point gives rise to one connected curve with traversal sequence S'' (with the same interlacement graph as S). We are not assured that S and S'' are equal. In fact, we are not even assured that a proper order of switching allows to obtain S' from S''.

Moreover, a cross-realizable sequence does not determine the cross curve itself up to an homeomorphism and different cross-realizable sequences may have the same interlacement graph (e.g. the sequences $(abcaefdcbefd)$ and $(acbaefdbcefd)$).

The figure bellow shows how a touch curve may be transformed into a bipartite chord diagram with the same interlacement (and conversely).



Hence, we have :

Proposition 2. *A sequence S is touch realizable if and only if its interlacement graph $\Lambda(S)$ is bipartite.* □

Theorem 3. *Let S be a sequence S, with any given order on the symbols. Then, S is cross realizable if and only if the sequence $S_n = S \circledcirc p_1 \circledcirc \ldots \circledcirc p_n$ obtained by successively D-switching the p_i has a bipartite interlacement graph.*

Proof. – Assume S is realized by a cross curve C. As a D-switch of a crossing point of a parametrized curve gives rise to two touching points (that will never become crossing points again), the curve C is iteratively transformed into a touch curve C_n. The traversal sequence S_n of C_n has hence a bipartite interlacement graph.

– Conversely, assume that S_n has a bipartite interlacement graph.
Let $S_i = S \circledcirc p_1 \circledcirc \ldots \circledcirc p_i$ denote the sequence obtained after the first i D-switches, we shall inductively construct (for i going from n to 0) a parameterized curve C_i, that realizes S_i, and such that the crossings of C_i are the p_j, with $j > i$. Then, the parameterized curve C_0 will be a cross curve realizing S.
As $\Lambda(S_n)$ is bipartite, there exists a touching curve C_n whose traversal sequence is S_n.
If p_i is of type 1, the suppression of p'_i and the a switch at p_i transforms p_i into a crossing point and gives rise to C_{i-1}, having $p_i, \ldots, p_n$ as crossing points and S_{i-1} as traversal sequence.
So, the proof will be complete if we prove that p_i is of type 1 in C_i, that is that p_i has been inverted an even number of times during the D-switch at $p_i, \ldots, p_n$: The symbol p_i and its twin p'_i are not interlaced in S_i, they are alternatively interlaced and non-interlaced after each further inversion and, if p_i has been last inverted by a switch at p_j, p_i (resp. p'_i) and p_j are interlaced in S_n. As $\Lambda(S_n)$ is bipartite, p_i and p'_i are not interlaced in S_n (else p_i, p'_i, p_j would define a triangle of $\Lambda(S_n)$). Hence, the symbol p_i has been inverted an even number of times.

□

Remark that a cross curve realizing the sequence S could be geometrically derived from a touch curve realizing the sequence S' obtained from S_n by suppressing all twinned letters by transforming each touching point into a crossing point.

4 Proof of Rosenstiehl's Theorem

In the following, two vertices u, v of a graph G with a vertex bipartition (A, B) are said to satisfy the property P if they have an odd number of common neighbors if and only if they are adjacent and belong to the same class (A or B).

Lemma 4. *Let G be a graph with a vertex bipartition A, B and let p be a vertex of G. Let $G' = G \circledcirc p$ and let A', B' be the vertex bipartition of G' defined by : $A' = A + N(p), B' = B + N(p)$ and assigning p' to the* *class of p. If G is eulerian and any pair u, v of vertices of G satisfies (P) (according to the bipartition A, B), then G' is eulerian and any pair u, v of vertices of G' satisfies (P) (with respect to the bipartition A', B').*

Proof. We have the following relationship between the neighborhood $N_{G'}$ in G' and the neighborhood N_G in G :

- $N_{G'}(u) = N_G(u)$, if u is not adjacent to p (in G or equivalently in G'),
- $N_{G'}(p') = N_{G'}(p) = N_G(p)$,
- $N_{G'}(u) = N_G(u) + u + N_G(p) + p'$, if u is adjacent to p.

In order to prove that G' is eulerian, we only have to check that the neighbors of p have an even degree : the parity of $N_{G'}(u) = N_G(u) + u + N_G(p) + p'$ is the sum of the parities of $N_G(u), \{u\}, N_G(p)$ and $\{p\}$ and hence is even.

Now, we shall prove that any pair of vertices u, v of G' satisfies (P), with respect to the bipartition A', B'. If u or v is p', we shall replace it by p as p and p' have the same neighbors, are not adjacent and belong to the same class (A', B').

If two vertices u, v are not adjacent or equal to p, then their adjacencies, their class and their number of common neighbors are the same in G and G'. Thus, the pair u, v satisfies (P).

If u is adjacent to p and v is not adjacent or equal to p, then

$$\begin{aligned} <N_{G'}(u), N_{G'}(v)> &= <N_G(u) + u + N_G(p) + p', N_G(v)> \\ &= <N_G(u), N_G(v)> + 1 \end{aligned}$$

As u and v belongs to the same class (A', B') if and only if they do not belong to the same class (A, B) and as they are adjacent, the pair u, v satisfies (P).

If u and v are both adjacent to p, then

$$\begin{aligned} <N_{G'}(u), N_{G'}(v)> &= <N_G(u) + u + N_G(p) + p', N_G(u) + v + N_G(p) + p'> \\ &= <N_G(u), N_G(v)> + <N(u), N(p)> + <N(v), N(p)> + 1 \end{aligned}$$

As u is adjacent to p, $<N(u), N(p)> = 1$ if and only if u and p belongs to the same class (A, B). So, $<N(u), N(p)> + <N(v), N(p)> + 1 = 1$ if and only if u and v do not belongs to the same class (A, B). As $<N_G(u), N_G(v)> = 1$ if and only if u and v are adjacent in G and belongs to the same class (A, B), $<N_{G'}(u), N_{G'}(v)> = 1$ if and only if u and v are not adjacent in G and belong to the same class (A, B), that is, if and only if they are adjacent in G' and belong to the same class (A', B'). Thus, the pair u, v satisfies (P). □

Lemma 5. *Let G be a graph with a vertex bipartition A, B and let p be a vertex of G. Let $G' = G \circledast p$ and let A', B' be the vertex bipartition of G' defined by : $A' = A + N(p), B' = B + N(p)$ and assigning p' to the class of p. If G' is eulerian and any pair u, v of vertices of G' satisfies (P) (with respect to the bipartition A', B'),then G is eulerian and any pair u, v of vertices of G satisfies (P) (with respect to the bipartition A, B).*

Proof. By Lemma 4, $G'' = G' \circledast p$ has the requested property and this property is still satisfied when deleting the two twins of p. □

Theorem 6 (Rosenstiehl). *A sequence S is cross realizable if and only if its interlacement graph $\Lambda(S)$ satisfy :*

- *$\Lambda(S)$ is eulerian,*
- *for any non-edge (p, p') of $\Lambda(S)$, $N(p) \cap N(p')$ is even,*
- *the set of the of the edges (p, p') of $\Lambda(S)$ such that $N(p) \cap N(p')$ is even is a cocycle of $\Lambda(S)$.*

Proof. The theorem may be restated as follows : A sequence S is cross realizable if and only if its interlacement graph $\Lambda(S)$ is eulerian and if there exists a bipartition A, B of the vertex set of $\Lambda(S)$ such that any pair u, v of vertices of $\Lambda(S)$ satisfies (P).

Consider any sequence $S_n = S \circledast p_1 \circledast \ldots \circledast p_n$ obtained by successively D-switching the symbols of S. According to Lemma 4, $\Lambda(S_n)$ is eulerian and has a bipartition A', B' such that any pair of vertices of $\Lambda(S_n)$ satisfies (P). As all the symbols have been twinned and as p and its twin p' have the same neighbors, any two vertices of $\Lambda(S_n)$ have an even number of common vertices. According to property (P), the graph $\Lambda(S_n)$ is bipartite. Then, from Theorem 3, S is cross realizable.

Conversely, if S is cross realizable, any sequence of D-switches gives rise to a sequence S' having a bipartite interlacement graph. This graph is eulerian (due to the doubling of each symbol) and a bipartition A, B induced by a bicoloration, is such that each pair of vertices satisfies (P). The theorem then follows from Lemma 5. □

5 Matroidal Interpretation

As we wanted to give a short self-contained proof, we did not introduce the usual concepts of binary matroids. In such a context, a proof could done, relying on the following properties : The graphs which satisfy the conditions given for $\Lambda(S)$ in Rosenstiehl's characterization are exactly the principal interlacement graph of some binary matroid M [14]. Any local complementation of the vertices of such a graph gives rise to a bipartite graph, which is the fundamental interlacement graph of M with respect to some base B of M [3]. The further condition that a principal interlacement graph is an interlacement graph (that is a circle graph) implies that the matroid M is planar and then, the principal interlacement graph corresponds to the interlacement of a left-right path of a planar realization of M [3].

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