Computing Hypercircles by Moving Hyperplanes

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Abstract

Let $\mathbb{K}$ be a field of characteristic zero, α algebraic of degree n over $\mathbb{K}$. Given a proper parametrization ψ of a rational curve $\mathcal{C}$, we present a new algorithm to compute the hypercircle associated to the parametrization ψ. As a consequence, we can decide if $\mathcal{C}$ is defined over $\mathbb{K}$ and, if not, to compute the minimum field of definition of $\mathcal{C}$ containing $\mathbb{K}$. The algorithm exploits the conjugate curves of $\mathcal{C}$ but avoids computation in the normal closure of $\mathbb{K}(\alpha)$ over $\mathbb{K}$.

1 Introduction

Let $\mathbb{K}(\alpha)$ be a computable characteristic zero field with factorization such that $\mathbb{K}$ is finitely generated over $\mathbb{Q}$ as a field and α is of degree n over $\mathbb{K}$.

Let $\psi(t) = (\psi_1(t), \ldots, \psi_m(t))$ be a proper parametrization of a rational spatial curve $\mathcal{C}$, where $\psi_i \in \mathbb{K}(\alpha)(t)$, $1 \leq i \leq m$. The reparametrization problem ask for methods to decide in $\mathcal{C}$ is defined or parametrizable over $\mathbb{K}$ and, if possible, compute a parametrization of $\mathcal{C}$ over $\mathbb{K}$.

In [1], the authors proposed a construction to solve this problem introducing a family of curves called hypercircles and avoiding any implicitization technique. Starting from the parametrization ψ, they construct an analog to Weil descente variety to compute a curve $\mathcal{U}$ called the *witness variety* or the *parametric variety of Weil*. This curve exists if and only if $\mathcal{C}$ is defined over $\mathbb{K}$ and we can obtain a parametrization of $\mathcal{C}$ with coefficients in $\mathbb{K}$ easily from a parametrization of $\mathcal{U}$ with coefficients in $\mathbb{K}$. Efficient algorithms to compute a parametrization of $\mathcal{U}$ with coefficients in $\mathbb{K}$ are studied in [7], provided we are able to find a point in $\mathcal{U}$ with coefficients over $\mathbb{K}$.

The definition of $\mathcal{U}$ is done under a parametric version of Weil's descente method. In the proper parametrization $\psi = (\psi_1, \ldots, \psi_m)$, $\psi_i \in \mathbb{K}(\alpha)(t)$ with coefficients in $\mathbb{K}(\alpha)$, we substitute $t = \sum_{i=0}^{n-1} \alpha^i t_i$, where $t_0, \ldots, t_{n-1}$ (where n is the degree of α over $\mathbb{K}$).

We can rewrite:

$$\psi_j\left(\sum_{i=0}^{n-1} \alpha^i t_i\right) = \sum_{i=0}^{n-1} \alpha^i \lambda_{ij}(t_0, \ldots, t_{n-1}), \lambda_{ij} = \frac{F_{ij}}{D} \in \mathbb{K}(t_0, \ldots, t_{n-1})$$

In this context we have the following definition:

Definition 1. *The parametric variety of Weil $\mathcal{Z}$ of the parametrization ψ is he Zariski closure of*

$$\{F_{ij} = 0 \mid 1 \le i \le n-1,\ 1 \le j \le N\} \setminus \{D = 0\} \subseteq \mathbb{F}^n.$$

Much is known about $\mathcal{Z}$, it is always a set of dimension 0 or 1. It is of dimension one exactly in the case that $\mathcal{C}$ is defined over $\mathbb{K}$ (See [1], [2]). In this case, $\mathcal{Z}$ contains exactly one component of dimension 1 that is the searched curve $\mathcal{U}$.

The computation of the curve $\mathcal{U}$ from its definition is unfeasible except for toy examples. The curve $\mathcal{U}$ is defined as the unique one dimensional component of a the difference of two varieties $\mathcal{A} - \mathcal{B}$. This already is a hard enough problem to look for alternatives, but this method also uses huge polynomials. If $\psi_i(t) = n_i(t)/d(t)$ and $d = d(\alpha, t) \in \mathbb{K}[\alpha, t]$. Let $M(x)$ be the minimal polynomial of α over $\mathbb{K}$. In the generic case, the denominator D is $D = Res_z(d(z, \sum_{i=0}^{n-1} z^i t_i), M(z))$ which is typically a dense polynomial of degree dn in n variables. Hence, the number of terms of the polynomial D alone is not polynomially bounded in n.

The aim of the article is to present an algorithm to compute the variety $\mathcal{U}$ that is polynomial in d and n and, if $\mathcal{C}$ is not defined over $\mathbb{K}$, to compute the smallest field $\mathbb{L}$, $\mathbb{K} \subseteq \mathbb{L} \subseteq \mathbb{K}(\alpha)$ that defines $\mathcal{C}$. The article is structured as follows. First we introduce in Section 2 the geometric construction that will allow us to derive an efficient algorithm. Then, we show in Section 3 how to compute efficiently some steps of the algorithm. Last, in Section 4, we study the complexity of the algorithm and some running times comparing with other approaches.

2 Synthetic construction of Hypercircles

The problem of parametrizing $\mathcal{C}$ over $\mathbb{K}$ can be translated to the problem of parametrizing $\mathcal{U}$. In the case that $\mathcal{C}$ can be parametrized over $\mathbb{K}$, then $\mathcal{U}$ is a very special curve called hypercircle.

Definition 2. *Let $\frac{at+b}{ct+d} \in \mathbb{K}(\alpha)(t)$ represent an isomorphism of $\mathbb{F}(t)$, $a, b, c, d \in \mathbb{K}(\alpha)$, $ad - bc \neq 0$. Write*

$$\frac{at+b}{ct+d} = \lambda_0(t) + \alpha\lambda_1(t) + \cdots + \alpha^{n-1}\lambda_{n-1}(t)$$

where $\lambda_i(t) \in \mathbb{K}(t)$. The hypercircle associated to $\frac{at+b}{ct+d}$ for the extension $\mathbb{K} \subseteq \mathbb{K}(\alpha)$ is the parametric curve in $\mathbb{F}^n$ given by the parametrization $(\lambda_0, \ldots, \lambda_{n-1})$.

If $\mathcal{C}$ cannot be parametrized over $\mathbb{K}$ and $\mathbb{K}$ is small enough (that means that it is finitely generated over $\mathbb{Q}$ as a field, that we can always assume without loss of generality), then there always exists an element β algebraic of degree 2 over $\mathbb{K}$ such that $[\mathbb{K}(\beta, \alpha) : \mathbb{K}(\alpha)] = n$ and $\mathcal{C}$ can be parametrized over $\mathbb{K}(\beta)$, see [12] for the details. In this situation $\mathcal{U}$ is a hypercircle for the extension $\mathbb{K}(\beta) \subseteq \mathbb{K}(\alpha, \beta)$. That is, there is an associated unit $\frac{at+b}{ct+d}$, but with $a, b, c, d \in \mathbb{K}(\beta)$.

Thus, the curve $\mathcal{U}$ is always a hypercircle for certain algebraic extension. So all the geometric properties of hypercircles studied in [6] hold for $\mathcal{U}$ except, maybe, the existence of a point in $\mathcal{U} \cap \mathbb{K}^n$. We will exploit the geometric properties of hypercircles to derive our algorithm. We start with the fact that $\mathcal{U}$ is always a rational normal curve in $\mathbb{F}^n$ defined over $\mathbb{K}$ (See [6]) and the synthetic construction of rational normal curves as presented in [5].

Let us recall the construction of conics by a pair of pencil of lines. Let $\mathfrak{L}(t)$ and $\mathfrak{F}(t)$ be two different pencils of lines in the plane with two different base points $l_0 \neq f_0$ and let C be a conic passing trough l_0 and f_0. Then, C induces an isomorphism $u : \mathfrak{L}(t) \to \mathfrak{F}(t)$ given by extending the map $u(\mathfrak{L}(t_0)) = \mathfrak{F}(s_0)$ if

$$\mathfrak{L}(t_0) \cap C - \{l_0\} = \mathfrak{F}(s_0) \cap C - \{f_0\}.$$

Conversely, an isomorphism u between $\mathfrak{L}(t)$ and $\mathfrak{F}(t)$ defines a line or a conic passing through the base points. There is a proper parametrization of this curve given by $t \mapsto \mathfrak{L}(t) \cap \mathfrak{F}(u(t))$.

Example 3. *Let $\mathcal{C} = x^2 + y^2 - 1$ be the unit circle. And take the pencils of lines that passes through the points at infinity of the circle* $[1 : i : 0], [1 : -i : 0]$. $\mathfrak{L}(t) = \{x + iy = t\}$*,* $\mathfrak{F}(t) = \{x - iy = t\}$*. In this case* $\mathcal{C} \cap \mathfrak{L}(t) = (\frac{t^2+1}{2t}, \frac{-it^2+i}{2t})$ *and* $\mathcal{C} \cap \mathfrak{F}(t) = (\frac{t^2+1}{2t}, \frac{it^2-i}{2t})$*. In this case, the isomorphism between the pencils is given by $u(t) = 1/t$. Now, let us take the isomorphism $u(t) = (t+i)/t$. Then, the conic defined by u from the two pencils of lines is $x^2+y^2-x-iy-i$. Which is a conic passing through the base points, although not defined over $\mathbb{Q}$.*

More generally, the same geometric construction applies to rational normal curves of degree $n > 2$ in $\mathbb{F}^n$ as explained in [5]. We only show the special case of this construction that is relevant for hypercircles. If $\mathcal{U}$ is a hypercircle, it is known that $\mathcal{U}$ can be parametrized by the pencil of hyperplanes $\mathfrak{L}_0 = \{\sum_{i=0}^{n-1} \alpha^i x_i = t\}$ [6]. This pencil of hyperplanes yield to a proper parametrization $\phi = (\phi_0(t), \ldots, \phi_{n-1}(t))$ of the hypercircle with coefficients in $\mathbb{K}(\alpha)$ that is called the *standard parametrization* of the hypercircle and has been studied with detail in [7]. Since the hypercircle is always a curve defined over $\mathbb{K}$, it is invariant under conjugation and it can also be parametrized by the conjugate pencil of hyperplanes.

Let us fix some notation. Let $\alpha = \alpha_0, \alpha_1, \ldots, \alpha_{n-1}$, the conjugates of α over $\mathbb{K}$ in $\mathbb{F}$. Let σ_i, $0 \leq i \leq n-1$ be $\mathbb{K}$-automorphisms of $\mathbb{F}$ such that $\sigma_i(\alpha) = \alpha_i$ and $\sigma_0 = Id$. If we have a rational function $f(t) \in \mathbb{K}(\alpha)(x_1, \ldots, x_r)$, we denote by $f^{\sigma_j} = \sigma_j(f) \in \mathbb{K}(\alpha_j)(x_1, \ldots, x_r)$ that results applying σ_j to the coefficients of f. If $\mathcal{C}$ is the original curve, then we denote by $\mathcal{C}^\sigma$ the conjugate curve $C^\sigma = \{\sigma(x) | x \in C\}$, where $\sigma(x)$ is applied component-wise. $\mathcal{C}^\sigma$ is clearly a rational curve with proper parametrization ψ^σ.

It is known [2] that $\mathcal{C}$ is defined over $\mathbb{K}$ if and only if $\mathcal{C} = \mathcal{C}^{\sigma_i}$ $1 \leq i \leq n-1$ if and only if ψ^{σ_i} parametrizes $\mathcal{C}$, $1 \leq i \leq n-1$.

The conjugate pencil of hyperplanes $\mathfrak{L}_j(t) = \{\sum_{i=0}^{n-1} \alpha_j^i x_i = t\}$, $1 \le j \le n-1$ also parametrizes $\mathcal{U}$, yielding the conjugate parametrization $\phi^{\sigma_j}(t) = \sigma_j(\phi(t))$.

The hypercircle then induces an isomorphism $u_j(t)$ between $\mathfrak{L}_0(t)$ and $\mathfrak{L}_j(t)$ given by $(\mathfrak{L}_0(t_0) \cap \mathcal{U}) - H = (\mathfrak{L}_j(u_j(t_0)) \cap \mathcal{U}) - H$ for all but finitely many parameters t_0, where H is the hyperplane at infinity of $\mathbb{P}(\mathbb{F})^n$. So $\phi(t) = \phi^{\sigma_j}(u_j(t))$, from which $u_j(t) = (\phi^{\sigma_j})^{-1} \circ \phi$. But, by construction, $(\phi^{\sigma_j})^{-1}(x_0, \ldots, x_{n-1}) = \sum_{i=0}^{n-1} \alpha_j^i x_i$ and $u_j(t) = \sum_{i=0}^{n-1} \alpha_j^i \phi_i(t)$. Conversely, a set of isomorphisms $u_j : \mathfrak{L}_0(t) \to \mathfrak{L}_j(t)$, $0 \le j \le n-1$, $u_0(t) = t$, defines a rational normal curve given by $t \to \bigcap_{i=0}^{n-1} \mathfrak{L}_j(u_j(t))$. So, we can recover the standard parametrization of the hypercircle if we know the isomorphisms u_j, $0 \le j \le n-1$, where $u_0(t) = t$. The standard parametrization ϕ is the unique solution of the Vandermonde linear system of equations:

$$\begin{pmatrix} 1 & \alpha & \ldots & \alpha^{d-1} \\ 1 & \alpha_2 & \ldots & \alpha_2^{d-1} \\ & & \ldots & \\ 1 & \alpha_n & \ldots & \alpha_n^{d-1} \end{pmatrix} \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_{n-1} \end{pmatrix} = \begin{pmatrix} u_0(t) = t \\ u_1(t) \\ \ldots \\ u_{n-1}(t) \end{pmatrix} \tag{1}$$

with coefficients on the normal closure of α over $\mathbb{K}$.

As in the planar case, if the automorphisms are generic enough, the curve $\mathcal{U}$ will be of degree n. In this case we say that $\mathcal{U}$ is a *primitive* hypercircle. There may be cases in which the curve $\mathcal{U}$ is of degree less than n. If this is the case, the degree of $\mathcal{U}$ must be a divisor of n and is related with the field of definition of the place of $\mathcal{C}$ corresponding to $\psi(t = \infty)$, as showed in [12].

The good news is that we can compute easily the automorphisms $u_j(t)$ from the parametrization $\psi(t)$ alone.

Theorem 4. *Let $\psi(t) \in \mathbb{K}(\alpha)(t)^m$ be a proper parametrization of $\mathcal{C}$ and assume that $\mathcal{C}$ is defined over $\mathbb{K}$. Let $\phi(t)$ be the standard parametrization of the associated hypercircle $\mathcal{U}$. Let σ_i be a $\mathbb{K}$-automorphism of $\mathbb{F}$. Let $\phi^{\sigma_i} = \sigma_i(\phi)$, $\psi^{\sigma_i} = \sigma_i(\psi)$ be the conjugate parametrizations and $u_{\sigma_i}(t) = (\phi^{\sigma_i})^{-1} \circ \phi$ be the conjugation isomorphism induced by $\mathcal{U}$ in the pencil of hyperplanes $\mathfrak{L}_0$ and $\mathfrak{L}_{\sigma_i}$. Then $u_{\sigma_i} = (\psi^{\sigma_i})^{-1} \circ \psi$.*

Proof. We identify $\mathcal{C}$ with the diagonal curve Δ in the variety $\mathcal{C} \times \mathcal{C}^{\sigma_1} \times \ldots \times \mathcal{C}^{\sigma_{n-1}}$, $\Delta = \{(x, \ldots, x) | x \in \mathcal{C}\}$ the hypercircle $\mathcal{U}$ is a curve such that the map

$$\begin{array}{ccc} \mathcal{U} & \to & \mathcal{C} \times \mathcal{C}^{\sigma_1} \times \ldots \times \mathcal{C}^{\sigma_{n-1}} \\ (x_0, \ldots, x_{n-1}) & \mapsto & \left(\psi(\sum_{j=0}^{n-1} x_j \alpha^j), \psi^{\sigma_1}(\sum_{j=0}^{n-1} x_j \alpha_1^j), \ldots, \psi^{\sigma_{n-1}}(\sum_{j=0}^{n-1} x_j \alpha_{n-1}^j) \right) \end{array}$$

Is a birational map between $\mathcal{U}$ and $\Delta = \mathcal{C}$. See [2] for the details. This means that $\psi(\sum_{j=0}^{n-1} x_j \alpha^j) = \psi^{\sigma_i}(\sum_{j=0}^{n-1} x_j \alpha_i^j)$ for the points of the hypercircle. If we plug the standard parametrization of the hypercircle in this equality, we get that

$$\psi(t) = \psi(\sum_{j=0}^{n-1} \phi_j \alpha^j) = \psi^{\sigma_i}(\sum_{j=0}^{n-1} \phi_j \alpha_i^j) = \psi^{\sigma_i}(u_{\sigma_i}(t))$$

From which $u_{\sigma_i} = (\psi^{\sigma_i})^{-1} \circ \psi$. $\square$

Hence the isomorphism u_j induced by the hypercircle in the pencil of hyperplanes $\mathfrak{L}(t)$ and $\mathfrak{L}_j(t)$ is the change of variables needed to transform the conjugate parametrization $\psi^{\sigma_j}(t)$ into $\psi(t)$. We can compute u_j using gcd.

Theorem 5. *Let $\psi_i(t) = n_i(t)/d_i(t)$ and $\psi_i^{\sigma_j}(t) = n_i^{\sigma_j}(t)/d_i^{\sigma_j}(t)$ be the numerators and denominators of ψ and ψ^j. Then, if $\mathcal{C}$ is defined over $\mathbb{K}$, the numerator of $s - u_j(t)$ is a polynomial of degree 1 in t and in s that is the common factor of the set of polynomials*

$$B_{\sigma_j} = \{n_i(t) \cdot d_i^{\sigma_j}(s) - n_i^{\sigma_j}(s) \cdot d_i(t), 1 \leq i \leq m\}.$$

On the other hand, if $\mathcal{C}$ is not defined over $\mathbb{K}$, there is an index $1 \leq j \leq n-1$ such that $\gcd(B_{\sigma_j}) = 1$.

Proof. This result follows directly from the geometric interpretation. First, assume that $\mathcal{C}$ is defined over $\mathbb{K}$. It is clear that the numerator of $s - u_j(t)$ is a common factor of the set B_{σ_j}. Let $f(t,s)$ be the gcd of B_{σ_j} and let $p = \psi(t_0) \in \mathcal{C}$ where t_0 is a generic evaluation of t. The roots of $f(t_0, s)$ are solutions of the system of equations $\psi_i^{\sigma_j}(s) = p_i$. But, since ψ^{σ_j} is birational, for all but finitely many t_0 there is only one solution, $(\psi^{\sigma_j})^{-1}(p)$. Hence, the degree of f with respect to s is one. By symmetry, the degree of f with respect to t is also one. It follows that f must be the numerator of $s - u(t)$.

Now, assume that $\mathcal{C}$ is not defined over $\mathbb{K}$. Then, there is an index j such that $\mathcal{C} \neq \mathcal{C}^{\sigma_j}$. In this situation, for all but finitely many evaluations $t = t_0$, the system of equations $\psi^{\sigma_j}(s) = \psi(t_0)$ has no solution. It follows that $\gcd(B_{\sigma_j}) = 1$. $\square$

So, we can compute $\mathbb{K}$-definability and the standard parametrization of the hypercircle $\mathcal{U}$ by the following method:

- For each conjugate α_j, Compute $a(t) + sb(t)$, the gcd of $n_i(t) \cdot d_i^{\sigma_j}(s) - n_i^{\sigma_j}(s) \cdot d_i(t), 1 \leq i \leq m$. If one of the gcd is one, then the curve is not defined over $\mathbb{K}$ and we are done.
- Set $u_j = -a(t)/b(t)$.
- Solve the linear system of equations (1) whose coefficients are rational functions in t with coefficients in the normal closure of $\mathbb{K}(\alpha)$.

However, computing these bivariate gcd are expensive and, moreover, in the worst case, we will have to solve a linear set of equations with coefficients in an extension of $\mathbb{K}$ of degree $n!$. Next section address the problem of how to perform this algorithm efficiently.

3 Efficient Computation of the Hypercircle

We have shown how to compute $u_\sigma(t)$ by computing the gcd of the polynomials in B_σ. We already now that, if $\mathcal{C}$ is $\mathbb{K}$-definable, the gcd has degree 1 in t and

s, so the best suited algorithms for computing the gcd seem to be interpolation algorithms. Since we are only interested in u_σ and this linear fraction is an automorphism of $\mathbb{P}^1(\mathbb{F})$, we only need to know the image of three points t_0, t_1, t_2 under u_σ. From Theorem 5, for almost all t_i, $u_\sigma(t_i) = (s_i)$ if and only if $\psi(t_i) = \psi^\sigma(s_i)$. Hence, each s_i is the common root of the polynomials:

$$\psi(t_i) \cdot d_j^\sigma(s) - n_j^\sigma(s), 1 \leq i \leq m$$

s_i that can be computed by means of gcd of univariate polynomials in $\mathbb{K}(\alpha, \sigma(\alpha))$.

If $\mathcal{C}$ is defined over $\mathbb{K}$ then only finitely many parameters t_k will fail to provide a valid s_k. Essentially the parameters t_k can fail if $\psi(t_k)$ is a singular point of the curve or if it cannot be attained by a finite parameter s by the parametrization ψ^σ.

On the other hand, if $\mathcal{C}$ is not defined over K, then there is an automorphism σ such that $\mathcal{C} \neq \mathcal{C}^\sigma$. For this permutation, there are only finitely many parameters t_k such that $\psi(t_k) \in \mathcal{C} \cap \mathcal{C}^\sigma$. Hence, if we want to follow this approach and do not depend on probabilistic algorithms that may fail or give wrong answers, we need bounds to detect that the curve is defined over $\mathbb{K}$ or not.

Theorem 6. *Let $\mathcal{C} \subseteq \mathbb{F}^m$ be a rational curve of degree d given by a parametrization $\psi \in (\mathbb{K}(\alpha))^m$. Let α_i be any conjugate of α over $\mathbb{K}$. Take $t_1, \ldots, t_k \in \mathbb{F}$ parameters then:*

- *If $\mathcal{C}$ is definable over $\mathbb{K}$, then we can compute u_i from three correct solutions of the system of equations $\psi^\sigma(s) = t_k$.*
- *If $\mathcal{C}$ is defined over $\mathbb{K}$, then at most $d^2 - 2d + n + 1$ parameters can fail to give a correct answer.*
- *If $\mathcal{C}$ is not defined over $\mathbb{K}$, then at most d^2 parameters t_k will give a fake answer s_k.*

Proof. We have to compute the inverse of the point $\psi(t_j)$ under the parametrization $\psi^{\sigma_i}(s)$. For each t_k, this computation is done using univariate gcd. If we want to restrict to affine points, we have to eliminate d potential parameters of the denominator of ψ. Then, for an affine point $\psi(t_j)$, there can only be one point that is not attained by a finite parameter of ψ^{σ_i}. Since we have $n-1$ possible conjugates, then there may be $n-1$ points that are not attained by a finite parameter in one of the conjugate parmetrizations. So, if we get two different parameters t_j such that $\psi(t_j)$ is well defined but that $\psi^{\sigma_i}(s) = t_j$ have no solution (the corresponding gcd is 1), then the curve is not defined over $\mathbb{K}$. Now, it may happen that the gcd is of degree > 1. This can only happen if the point is singular in $\mathcal{C}$. Since $\mathcal{C}$ is of genus 0 and degree d, it can have at most $(d-1)(d-2)/2$ singularities. The number of different parameters whose image is a singularity is maximal if every singularity is ordinary. We have to maximize

$$\sum_{p \in sing(C)} mult_p(C)$$

subject to

$$\sum_{p\in sing(C)} mult_p(C)(mult_P(C)-1) = (d-1)(d-2)$$

See [9] Theorem 2.60 for details. But clearly, for any singular point $mult_p(C) \leq mult_p(C)(mult_P(C)-1)$ So $\sum_{p\in sing(C)} mult_p(C) \leq (d-1)(d-2)$ and the equality is attained if every singularity is an ordinary double point.

Thus, the maximal number of parameters that cannot be used to compute u_i is bounded by d parameters corresponding to the points at infinity plus $n-1$ points that might not be attained by a finite parameter in a conjugate parametrization ψ^σ plus $(d-1)(d-2)$ parameters whose image are singular points. This gives the bound $d^2-2d+n+1$.

Suppose now that $\mathcal{C}$ is not defined over $\mathbb{K}$. Let σ_i be such that $\mathcal{C} \neq \mathcal{C}^{\sigma_i}$. A parameter t_0 gives a fake answer for computing u_i if $\psi(t_0)$ is smooth in C^{σ_i} and is attained by a unique parameter s_0 by ψ^{σ_i}. But, by Bezout, $\mathcal{C}\cap\mathcal{C}^\sigma$ contains at most d^2 different points. So, there can be at most d^2 such bad parameters. $\square$

Remark 7. *In order to check that a parameter t_k is a good parameter or not we can do the following:*

- *If t_k is a root of the denominator of ψ, then t_k is a bad parameter.*
- *If $\gcd(\psi(t_k)\cdot d_i^\sigma(s) - n_i^\sigma(s), 1 \leq i \leq m) = 1$, then it is a bad parameter. It is a point that is not attained by the parametrization ψ^σ. If $\mathcal{C}$ is defined over $\mathbb{K}$ there can be at most one bad parameter that happens to be in this case that corresponds to $\psi^\sigma(t=\infty)$.*
- *If $\deg(\gcd(\psi(t_k)\cdot d_i^\sigma(s) - n_i^\sigma(s), 1 \leq i \leq m)) > 1$ then t_k is a bad parameter, since $\psi(t_k)$ is a singular point.*
- *If $\deg(\gcd(\psi(t_k)\cdot d_i^\sigma(s) - n_i^\sigma(s), 1 \leq i \leq m)) = 1$ but $\psi(t_k) = \psi^\sigma(\infty)$ then t_k is a bad parameter, $\psi(t_k)$ is singular.*
- *If $\deg(\gcd(\psi(t_k)\cdot d_i^\sigma(s) - n_i^\sigma(s), 1 \leq i \leq m)) = 1$ and $\psi(t_k) \neq \psi^\sigma(\infty)$ then t_k is a good parameter, we compute s_k solving the linear equation in s given by the* gcd.

Hence, if $\mathcal{C}$ is defined over $\mathbb{K}$, we can compute each u_j by interpolation. We will need at most $d^2-2d+n+1+3 = d^2-2d+n+4$ parameters. In practice however, we will almost always need only 3 parameters. Note also that if we choose the parameters in $\mathbb{K}$, then all computations needed to compute u_i are done in $\mathbb{K}(\alpha,\alpha_i)$, that is a extension of degree bounded by $n(n-1)$.

If $\mathcal{C}$ is not defined over $\mathbb{K}$ it can happen two things while trying to compute u_j. With high probability, we may find two different parameters such that $\gcd(\psi(t_k)\cdot d_i^\sigma(s) - n_i^\sigma(s), 1 \leq i \leq m) = 1$ and this is a certificate that the curve is not defined over $\mathbb{K}$. On the other hand, we may succeed computing u_j. This may happen if $\mathcal{C} = \mathcal{C}^{\sigma_j}$ for this specific σ_j or if we have chosen three parameters t_k such that $\psi(t_k) \in \mathcal{C} \cap \mathcal{C}^{\sigma_j}$. So, if we have computed all the linear fractions $u_j(t)$ but we want a certificate that $\mathcal{C}$ is defined over $\mathbb{K}$, we only need to check that $\psi(t) = \psi^{\sigma_j}(u_j(t))$, $1 \leq i \leq n$. In the case that computing this composition may be expensive, we can try to check the equality evaluating in several parameters t. $\psi(t)$ and $\psi^{\sigma_j}(u_j(t))$ are rational functions of degree d, so if they agree on $2d+1$ parameters where both parametrizations are defined, then $\psi(t) = \psi^{\sigma_j}(y_j(t))$ and $\mathcal{C} = \mathcal{C}^{\sigma_j}$. But there are d parameters where $\mathcal{C}$ is not defined and other d where $\mathcal{C}^{\sigma_i}$ is not defined. So, if we want a certificate that $\mathcal{C} = \mathcal{C}^{\sigma_j}$ by evaluation, we will need to try at most $4d+1$ parameters in the worst case. So $(n-1)(4d+1)$ evaluations to check all conjugates.

Example 8. *Let us show that the bounds given can be easily proven to be sharp if we allow the parameters to be in $\mathbb{F}$ and $d \geq n$. Let $\mathbb{K}(\alpha)$ be normal over $\mathbb{K}$ of degree n and $\sigma_1, \ldots, \sigma_{n-1}$ be $\mathbb{K}$-automorphisms that send α onto its conjugates. The common denominator of the parametrization of the curve will be $g = (t+1)\ldots(t+d)$ so that the parameters $-1, \ldots, -d$ will fail in the algorithm. Let us write a component as $f(t) = (\alpha t^d + a_{d-1}t^{d-1} + \ldots + a_1 t + a_0)/g(t)$, where the a_i are indeterminates. Impose the conditions $f(i) = \sigma_i(\alpha)$. This is a linear system of equations in the a_i representing an interpolation problem. We have $n-1$ conditions and d unknowns in the system and $n-1 < d$. Hence, there are infinitely many solutions to the system and we can take two generic solutions $f_1(t), f_2(t)$. The curve $\psi(t) = (f_1(t), f_2(t))$ will fail to give a correct answer for $t = -1, \ldots, -d$ due to the denominator and for $t = i$, $i = 1, \ldots, n-1$ because $\psi(t = \infty) = (\alpha, \alpha)$, so $\psi^\sigma(t = \infty) = (\sigma(\alpha), \sigma(\alpha)) = \psi(i)$. Finally, if we have chosen f_1, f_2 generic, the only singularities of ψ will be simple nodes in the affine plane. Thus, there will be $(d-1)(d-2)$ parameters that will yield to a singularity.*

For a specific example, take $\mathbb{K} = \mathbb{Q}$, α a primitive $5-th$ root of unity, so that $n = 4$. Let the degree be $d = 4$. If we perform the construction above, we get the relations in the coefficients of f:

$$a_0 = -6a_3 + (1440\alpha^3 + 1080\alpha^2 + 1044\alpha + 1920)$$

$$a_1 = 11a_3 + (-1740\alpha^3 - 1440\alpha^2 - 1380\alpha - 2700)$$

$$a_2 = -6a_3 + (420\alpha^3 + 360\alpha^2 + 335\alpha + 780)$$

If we compute f_0 and f_1 substituting a_3 by 0 and 1 respectively, we get the parametrization $\phi(f_0, f_1)$ of a rational curve of degree 4 with three nodes, such that the nodes are attained by the roots of $t^6 + (-420\alpha^3 + 60\alpha^2 - 90\alpha - 102)t^5 + (-59220\alpha^3 - 171720\alpha^2 + 85110\alpha - 214952)t^4 + (688980\alpha^3 + 1237740\alpha^2 - 450750\alpha + 1759626)t^3 + (-2309580\alpha^3 - 3135240\alpha^2 + 714450\alpha - 4869077)t^2 + (2877600\alpha^3 + 3308280\alpha^2 - 391560\alpha + 5387628)t + (-1197360\alpha^3 - 1231920\alpha^2 + 42840\alpha - 2063124)$.

Now, we show how to avoid in some cases some computations of u_j using conjugation.

Proposition 9. *Assume that $\mathcal{C}$ is defined over $\mathbb{K}$. Let $\alpha_i \neq \alpha_j$ be two conjugates of α over $\mathbb{K}$. Suppose that α_i, α_j are also conjugated over $\mathbb{K}(\alpha)$ and that τ is a $\mathbb{K}(\alpha)$-automorphism of $\mathbb{F}$ such that $\tau(\alpha_i) = \alpha_j$. Then $\tau(u_i) = u_j$.*

Proof. All operations to compute u_j are evaluating rational functions with coefficients in $\mathbb{K}(\alpha, \alpha_i)$ at parameters in $\mathbb{K}$ (or even $\mathbb{Z}$), compute gcd of univariate polynomials with coefficients also in $\mathbb{K}(\alpha, \alpha_i)$ and solving a linear system of equations. These operations commute with conjugation by σ. Thus, if τ is a $\mathbb{K}(\alpha)$-automorphism such that $\tau(\alpha_i) = \alpha_j$, we can conjugate by τ at every step of the method to compute u_i. Hence, $\tau(u_i) = u_j$. □

If the Galois group of $\overline{\mathbb{K}(\alpha)}$ over $\mathbb{K}$ is the permutation group S_n, we will only need to compute one automorphism u_i making computations in a number field of degree $n(n-1)$. On the other extreme, if $\mathbb{K} \subseteq \mathbb{K}(\alpha)$ is normal, we will have to compute $n-1$ different automorphisms u_i, but the computations will be in the smaller field $\mathbb{K}(\alpha)$.

Now, we show how to avoid computing in the normal closure of $\mathbb{K}(\alpha)$ over $\mathbb{K}$ to solve the linear system of equations 1. This system is given by a Vandermonde matrix, so we are dealing with an interpolation problem. If the standard parametrization searched is $(\phi_0, \dots, \phi_{n-1})$. Then, the polynomial

$$F(x) = \phi_0 + \phi_1 x + \ldots + \phi_{n-1} x^{n-1} \in \mathbb{K}(\alpha)(t)[x]$$

is the unique polynomial of degree at most $n-1$ such that $F(\alpha_i) = u_i(t)$, $0 \leq i \leq n-1$. F can be computed by Lagrange interpolation

$$F(x) = \sum_{i=0}^{n-1} \frac{(x-\alpha_0)\ldots(x-\alpha_{i-1})(x-\alpha_{i+1})\ldots(x-\alpha_{n+1})}{(\alpha_i-\alpha_0)\ldots(\alpha_i-\alpha_{i-1})(\alpha_i-\alpha_{i+1})\ldots(\alpha_i-\alpha_{n-1})} u_i(t)$$

Let us take a look at each term:

$$\frac{(x-\alpha_0)\ldots(x-\alpha_{i-1})(x-\alpha_{i+1})\ldots(x-\alpha_{n-1})}{(\alpha_i-\alpha_0)\ldots(\alpha_i-\alpha_{i-1})(\alpha_i-\alpha_{i+1})\ldots(\alpha_i-\alpha_{n-1})}$$

The numerator is $M(x)/(x-\alpha_i) = m(\alpha_i, x)$, where $M(x)$ is the minimal polynomial of α over $\mathbb{K}$ and the denominator is $m(\alpha_i, \alpha_i) = M'(\alpha_i)$. For each conjugacy class $\{\alpha_{i_1}, \dots, \alpha_{i_j}\}$ of roots of $M(x)$ over $\mathbb{K}(\alpha)$, we have that

$$\sum_{k=1}^{j} \frac{m(\alpha_{i_k}, x)}{m(\alpha_{i_k}, \alpha_{i_k})} u_{i_k}(t) = trace \frac{m(\alpha_{i_1}, x)}{m(\alpha_{i_1}, \alpha_{i_1})} u_{i_1}(t).$$

Where the trace is computed for the extension $\mathbb{K}(\alpha, t, x) \subseteq \mathbb{K}(\alpha, t, x)(\alpha_i)$. Hence, we need to compute only one term of the Laurent interpolation for each conjugacy class of roots of $M(x)$ over $\mathbb{K}(\alpha)$. These conjugacy classes are determined by the factorization of $M(x)$ in $\mathbb{K}(\alpha)[x]$.

Remark 10. *To compute fast the trace of* $v = \frac{m(\alpha_i,x)}{m(\alpha_i,\alpha_i)} u_i \in \mathbb{K}(\alpha,t,\alpha_i)[x]$*, first, we can compute the Newton sums* $\sum_{k=1}^{j} \alpha_{i_j}^{l}, 1 \leq l \leq n-1$ *from the minimal polynomial of* α_{i_1} *over* $\mathbb{K}(\alpha)$*. If the coefficients of* v *are polynomials in* t*, we compute easily the trace of* v *computing the trace of each coefficient of* v*. If the coefficients of* v *are not polynomials in* t*, we can write* v *as* $n/(t+b)$*,* $b \in \mathbb{K}(\alpha,\alpha_i)$*,* $n \in \mathbb{K}(\alpha,\alpha_i)[t]$*. This is due to the fact that the variable* t *only appears on the term* u_i *and it is a linear fraction. Now, let* $g(t)$ *be the minimal polynomial of* $-b$ *over* $\mathbb{K}(\alpha)$ *and* $g_1(t) = g(t)/(t+b) \in \mathbb{K}(\alpha,\alpha_i)[t]$*. Then* $v = n/(t+b) = (n \cdot g_1(t))/g(t)$ *and* $trace(v) = trace(n \cdot g_1)/g(t)$ *can be easily computed.*

Thus, we can compute the polynomial F (i.e. the standard parametrization) computing gcd and traces and norms in some fields of the form $\mathbb{K}(\alpha,\alpha_i)$. To sum up, our algorithm to compute the standard parametrization of $\mathcal{U}$ is the following.

Algorithm 11. *Input: A curve* $\mathcal{C}$ *given by a proper parametrization* $\psi(\alpha,t)$ *with coefficients in* $\mathbb{K}(\alpha)$*.*

Output: Either $\mathcal{C}$ is not defined over $\mathbb{K}$ *or* ϕ*, the standard parametrization of the hypercircle associated to* $\psi(t)$*.*

1. *Set* $M(x)$ *the minimal polynomial of* α *over* $\mathbb{K}$*.*
2. *Set* $m(\alpha,x) = M(x)/(x-\alpha) \in \mathbb{K}(\alpha)[x]$*.*
3. *Compute* $m(\alpha,x) = f_1(x)\cdots f_r(x)$ *the factorization of* $m(\alpha,x)$ *over* $\mathbb{K}(\alpha)$*.*
4. *Set* $F = \frac{m(\alpha,x)}{m(\alpha,\alpha)} t \in \mathbb{K}(\alpha,t)[x]$*.*
5. *For* $1 \leq i \leq r$ *do*
   (a) *Set* α_i *a root of* $f_i(x)$*.*
   (b) *Set* $\psi^{\sigma_i}(t) = \psi(\alpha_i,t)$ *the parametrization of the curve* C^{σ_i}*.*
   (c) *Compute three good parameters* t_1,t_2,t_3 *in the sense of remark 7.*
   (d) *If two parameters* t_i*,* t_j *are found such that* $\psi(t_i)$ *and* $\psi(t_j)$ *are well defined but not attained by* ψ^{σ_i} *then Return* $\mathcal{C}$ is not defined over $\mathbb{K}$.
   (e) *Compute* s_k *such that* $\psi(t_k) = \psi^{\sigma_i}(s_k)$*,* $1 \leq k \leq 3$*.*
   (f) *Compute* $u_i(t) = \frac{at+b}{ct+d}$ *the linear fraction such that* $u(t_k) = s_k$*.*
   (g) *If* $\psi \neq \psi^{\sigma_i}(u_i)$ *the Return* $\mathcal{C}$ is not defined over $\mathbb{K}$.
   (h) *Compute* $v = m(\alpha_i,x)/m(\alpha_i,\alpha_i) \cdot u_i(t) \in \mathbb{K}(\alpha,t,\alpha_i)[x]$*.*
   (i) *Compute* $w = trace(v)$ *for the extension* $\mathbb{K}(\alpha,t,x) \subseteq \mathbb{K}(\alpha,t,x)(\alpha_i)$*.*
   (j) *Set* $F = F + w \in \mathbb{K}(\alpha,t)[x]$*.*
6. *Write* $F = \phi_0(t) + \phi_1(t)x + \ldots + \phi_{n-1}(t)x^{n-1}$*.*
7. *Return* $\phi = (\phi_0,\ldots,\phi_{n-1})$*.*

Example 12. *Now we present a full small example of the algorithm. Let* $\mathbb{K} = \mathbb{Q}$, α *a root of* $M(x) = x^4 - 2$, *consider the proper parametrization* ψ *of a plane curve:*
$x = ((11\alpha^3+15\alpha^2+9\alpha+11)t^3+(7\alpha^3+14\alpha^2+14\alpha+7)t^2+(\alpha^3+2\alpha^2+4\alpha+1)t)/D$
$y = ((15\alpha^3 + 9\alpha^2 + 11\alpha + 22)t^3 + (25\alpha^3 + 29\alpha^2 + 16\alpha + 25)t^2 + (9\alpha^3 + 18\alpha^2 + 15\alpha + 9)t + \alpha^3 + 2\alpha^2 + 4\alpha + 1)/D$,
with $D = (7t^3+(12\alpha^3+3\alpha^2+6\alpha+12)t^2+(6\alpha^3+12\alpha^2+3\alpha+6)t+\alpha^3+2\alpha^2+4\alpha+1)$.

Now, $M(x) = (x-\alpha)(x+\alpha)(x^2+\alpha^2)$ *is the factorization of* $M(x)$ *in* $\mathbb{K}(\alpha)[x]$. $m(\alpha, x) = (x + \alpha)(x^2 + \alpha^2)$ *and* $m(\alpha, \alpha) = 4\alpha^3 = M'(\alpha)$. *start with* $F = \frac{m(\alpha,x)}{m(\alpha,\alpha)}t = 1/8(\alpha x^3 t + \alpha^2 x^2 t + \alpha^3 x t + 2t)$.

From the factors of $m(x)$ *we have two conjugacy classes of roots of* m *over* $\mathbb{K}(\alpha)$. *The first one is* $\{-\alpha\}$. *Let* σ *be a* $\mathbb{Q}$*-automorphism such that* $\sigma(\alpha) = -\alpha$. *Hence, we consider the conjugate parametrization* ψ^σ*:*
$x = ((-11\alpha^3 + 15\alpha^2 - 9\alpha + 11)t^3 + (-7\alpha^3 + 14\alpha^2 - 14\alpha + 7)t^2 + (-\alpha^3 + 2\alpha^2 - 4\alpha + 1)t)/D_1$,
$y = ((-15\alpha^3 + 9\alpha^2 - 11\alpha + 22)t^3 + (-25\alpha^3 + 29\alpha^2 - 16\alpha + 25)t^2 + (-9\alpha^3 + 18\alpha^2 - 15\alpha + 9)t - \alpha^3 + 2\alpha^2 - 4\alpha + 1)/D_1$, *with* $D_1 = (7t^3 + (-12\alpha^3 + 3\alpha^2 - 6\alpha + 12)t^2 + (-6\alpha^3 + 12\alpha^2 - 3\alpha + 6)t - \alpha^3 + 2\alpha^2 - 4\alpha + 1)$.

We have to compute the automorphism u_σ *such that* $\psi(t) = \psi^\sigma(u_\sigma(t))$. *we evaluate* $(\psi^\sigma)^{-1}(\psi(t_k))$ *and obtain:*

$$\psi(0) = \psi^\sigma(0)$$

$$\psi(1) = \psi^\sigma(8/31\alpha^3 - 4/31\alpha^2 + 2/31\alpha - 1/31)$$

$$\psi(2) = \psi^\sigma(128/511\alpha^3 - 32/511\alpha^2 + 8/511\alpha - 2/511)$$

Hence, $u_\sigma = \frac{at+b}{ct+d}$ *is such that* $u_\sigma(0) = 0$, $u_\sigma(1) = 8/31\alpha^3 - 4/31\alpha^2 + 2/31\alpha - 1/31$, $u_\sigma(2) = 128/511\alpha^3 - 32/511\alpha^2 + 8/511\alpha - 2/511$. *We can compute* $u(t) = \frac{at+b}{ct+d}$ *by solving a linear homogeneous system of equations and get the solution*

$$u_\sigma(t) = \frac{\alpha^3 t}{4t + \alpha^3}$$

In this case $\psi^\sigma(u_\sigma) = \psi$, *so* $C = C^\sigma$. *We can update* F *by adding:*

$$m(-\alpha, x)/m(-\alpha, -\alpha)u_\sigma(t) = \frac{-x^3 t + \alpha x^2 t - \alpha^2 x t + \alpha^3 t}{16t + 4\alpha^3}$$

So now:

$$F = \frac{\alpha x^3 t^2 + \alpha^2 x^2 t^2 + \alpha x^2 t + \alpha^3 x t^2 + 2t^2 + \alpha^3 t}{8t + 2\alpha^3}$$

For this root, all operations are done in $\mathbb{K}(\alpha)$ *since* $\sigma(\alpha) = -\alpha \in \mathbb{K}(\alpha)$.

Now, we have to deal with the roots of $x^2+\alpha^2$. *Let* β *be a root of* $x^2+\alpha^2$ *and* τ *a* $\mathbb{Q}$*-automorphism such that* $\tau(\alpha) = \beta$. *Consider the conjugate parametrization* ψ^τ*:* $x = (((-11\alpha^2+9)\beta - 15\alpha^2+11)t^3 + ((-7\alpha^2+14)\beta - 14\alpha^2+7)t^2 + ((-\alpha^2+4)\beta - 2\alpha^2+1)t)/D_2$, $y = (((-15\alpha^2+11)\beta - 9\alpha^2+22)t^3 + ((-25\alpha^2+16)\beta - 29\alpha^2+25)t^2 + ((-9\alpha^2+15)\beta - 18\alpha^2+9)t + (-\alpha^2+4)\beta - 2\alpha^2+1)/D_2$, *where* $D_2 =$

$7t^3+((-12\alpha^2+6)\beta-3\alpha^2+12)t^2+((-6\alpha^2+3)\beta-12\alpha^2+6)t+(-\alpha^2+4)\beta-2\alpha^2+1$. *In this case, we are taking the relative base* $\{\alpha^i\beta^j \mid 0 \leq i \leq 3, 0 \leq j \leq 1\}$ *of* $\mathbb{Q}(\alpha,\beta)$ *over* $\mathbb{Q}$. *Now we compute* u_τ *such that* $\psi(t) = \psi^\tau(u(t))$. *for this*

$$\psi(0) = \psi^\tau(0)$$

$$\psi(1) = \psi^\tau((2/9\alpha^2 - 2/9\alpha + 1/9)\beta + 2/9\alpha^3 - 1/9\alpha + 1/9)$$

$$\psi(2) = \psi^\tau((32/129\alpha^2 - 16/129\alpha + 4/129)\beta + 32/129\alpha^3 - 4/129\alpha + 2/129)$$

From this data, we can compute:

$$u_\tau(t) = \frac{t}{(\alpha-\beta)t+1}$$

If γ *is the other root of* $x^2+\alpha^2$ *(i.e.* $\gamma = -\beta$*) and* δ *is a* $\mathbb{Q}$*-automorphism such that* $\delta(\alpha) = \gamma$, *then* $u_\gamma(t) = t/(\alpha-\gamma)t+1$. *We have to compute the trace of*

$$v = \frac{m(\beta,x)}{m(\beta,\beta)}u_\tau(t) = \frac{\beta x^3 t - \alpha^2 x^2 t - \alpha^2\beta x t + 2t}{(-8\beta+8\alpha)t+8}$$

over $\mathbb{Q}(\alpha,t)$. *This is done using the technique described in Remark 10.*

$$trace(v) = \frac{-\alpha^2x^3t^2 - \alpha^3x^2t^2 - \alpha^2x^2t + 2xt^2 + 2\alpha t^2 + 2t}{8\alpha^2t^2 + 8\alpha t + 4}$$

To compute this part, we have made computation in $\mathbb{Q}(\alpha,\beta)$. *We add* $trace(v)$ *to* F *and get*

$$F = \phi_0 + \phi_1 x + \phi_2 x^2 + \phi_3 x^3$$

where

$$\phi_0 = \frac{2t^4+3\alpha^3t^3+3\alpha^2t^2+\alpha t}{8t^3+6\alpha^3t^2+4\alpha^2t+\alpha}, \phi_1 = \frac{\alpha^3t^4+2\alpha^2t^3+\alpha t^2}{8t^3+6\alpha^3t^2+4\alpha^2t+\alpha},$$

$$\phi_2 = \frac{\alpha^2t^4+\alpha t^3}{8t^3+6\alpha^3t^2+4\alpha^2t+\alpha}, \phi_3 = \frac{\alpha t^4}{8t^3+6\alpha^3t^2+4\alpha^2t+\alpha}$$

And $\phi = (\phi_0,\phi_1,\phi_2,\phi_3)$ *is the standard parametrization of the hypercircle associated to* ψ.

So far, Algorithm 11 only computes the hypercircle $\mathcal{U}$. The algorithm is able to detect if $\mathcal{C}$ is not defined over $\mathbb{K}$, but apart from that it does not provide much more useful information. In the rest of the section, we show that, if $\mathcal{C}$ is not defined over $\mathbb{K}$, how can we compute the minimum field $\mathbb{L}$ such that $\mathbb{K} \subseteq \mathbb{L} \subseteq \mathbb{K}(\alpha)$ and $\mathcal{C}$ is defined over $\mathbb{L}$. Note that $\mathbb{K}(\alpha)$ always is a field of definition of $\mathcal{C}$, so the existence of $\mathbb{L}$ is always guaranteed.

Theorem 13. *Let* $\mathcal{C}$ *be a curve not* $\mathbb{K}$*-definable but* $\mathbb{K}(\alpha)$*-parametrizable. Let* $\mathbb{L}$ *be the minimum field of definition of* $\mathcal{C}$ *containing* $\mathbb{K}$. $\mathbb{K} \subseteq \mathbb{L} \subseteq \mathbb{K}(\alpha)$. *Then* $\mathbb{L}$ *is the subfield of the normal closure* $\overline{\mathbb{K}(\alpha)}$ *over* $\mathbb{K}$ *that is fixed by the* $\mathbb{K}$*-automorphisms* σ *of* $\overline{\mathbb{K}(\alpha)}$ *such that* $\mathcal{C} = \mathcal{C}^\sigma$.

Proof. First, we recall that the intersection of fields of definition of $\mathcal{C}$ is a field of definition of $\mathcal{C}$. Hence, since $\mathbb{K}(\alpha)$ is a field of definition, there always exists a minimum field of definition $\mathbb{L}$ of $\mathcal{C}$ containing $\mathbb{K}$.

From [2] it follows that if $\mathbb{L}_1 \subseteq \mathbb{L}_2$ is any algebraic finite normal extension and $\mathbb{L}_2$ is a field of definition of $\mathcal{C}$, then $\mathbb{L}_1$ is a field of definition of $\mathcal{C}$ if and only if $\mathcal{C} = \mathcal{C}^\sigma$ for all $\sigma \in Aut(\mathbb{L}_2/\mathbb{L}_1)$.

Let $G = \{\sigma \in Aut(\overline{\mathbb{K}(\alpha)}/\mathbb{K}) \mid \mathcal{C}^\sigma = \mathcal{C}\}$. Clearly, G is a subgroup of $Aut(\overline{\mathbb{K}(\alpha)}/\mathbb{K})$. This follows from the fact that $(C^\sigma)^\tau = C^{\tau\circ\sigma}$. Let $\mathbb{L}$ be the subfield of $\overline{\mathbb{K}(\alpha)}$ that is fixed by G. $\mathbb{L} \subseteq \overline{\mathbb{K}(\alpha)}$ is a normal extension and, if σ is a $\mathbb{L}$-automorphism of $\mathbb{K}(\alpha)$ then $\sigma \in G$ so $\mathcal{C} = \mathcal{C}^\sigma$. In this conditions, $\mathbb{L}$ is a field of definition of $\mathcal{C}$. Moreover, it is the smallest field of definition of $\mathcal{C}$ containing $\mathbb{K}$. If $\mathbb{K} \subseteq \mathbb{L}_1 \subsetneq \mathbb{L}$ is a subfield of $\mathbb{L}$, then G_1, the set of $\mathbb{L}_1$-automorphisms of $\overline{K(\alpha)}$, is $G_1 \supsetneq G$. Hence, there is an automorphism $\tau \in G_1 \setminus G$. But then $\mathcal{C} \neq \mathcal{C}^\tau$ and $\mathbb{L}_1$ cannot be a field of definition of $\mathcal{C}$. Now, since $\mathbb{K}(\alpha)$ is also a field of definition of $\mathcal{C}$, then $\mathbb{L} \subseteq \mathbb{K}(\alpha)$. ☐

If $\sigma_0 = Id, \sigma_1, \ldots, \sigma_{n-1}$ are the automorphisms defined in Section 2, then for any $\sigma \in Aut(\mathbb{K}(\alpha)/\mathbb{K})$, it happens that $\mathcal{C}^\sigma = \mathcal{C}^{\sigma_i}$ for some i, $0 \leq i \leq n-1$. Hence

$$\mathbb{L} = \bigcap_{\substack{0 \leq i \leq n-1 \\ C = C^{\sigma_i}}} \{x \in \mathbb{K}(\alpha) \mid \sigma_i(x) = x\}$$

If $\mathcal{C}$ is not defined over $\mathbb{K}$, we compute in step 5 of Algorithm 11 the set of automorphism σ_i such that $\mathcal{C} = \mathcal{C}^{\sigma_i}$. For any such i, let m be the degree of α_i over $\mathbb{K}(\alpha)$. If $x \in \mathbb{K}(\alpha)$, we can write $\sigma_i(x) = \sum_{j=0}^{m-1} = l_i\alpha_i^j$, where $l_i \in \mathbb{K}(\alpha)$. x is σ_i invariant if and only if $x = l_0$, $l_i = 0$, $1 \leq i \leq m-1$. This provide a set of $\mathbb{K}$-linear equations in the coordinates of x in $\mathbb{K}(\alpha) \equiv \mathbb{K}^n$. Note also that if α_i and α_j are conjugate over $\mathbb{K}(\alpha)$, the equations imposed by σ_i and σ_j are the same. Hence, we only need to compute them once for each set of conjugate roots of $M(x)$ over $\mathbb{K}(\alpha)$. Solving the system of linear equations provide a base of $\mathbb{L}$ as a $\mathbb{K}$-subspace of $\mathbb{K}(\alpha)$. From this equation, we may reapply Algorithm 11 but to the extension $\mathbb{L} \subseteq \mathbb{K}(\alpha)$. In this case we already have computed the automorphisms u_i so we can reuse this computation.

4 Complexity and Running Time

We now compute the complexity of Algorithm 11 in terms of number of operations over the ground field $\mathbb{K}$. The analysis is by no means sharp, we only intend to prove that there is a polynomial bound and that the main obstacle is the degree of α over $\mathbb{K}$.

Theorem 14. *Let $\mathbb{K}$ be a computable field with factorization of characteristic zero. α algebraic of degree n over $\mathbb{K}$ of minimal polynomial $M(x)$. Let $\psi(t) = (\psi_0, \ldots, \psi_{m-1})$ be a proper parametrization of a spatial curve $\mathcal{C}$ with coefficients in $\mathbb{K}(\alpha)$. Then the number of operations over $\mathbb{K}$ of Algorithm 11 is bounded by $K + \mathcal{O}(md^5n^8)$ where K is the time needed to factor $M(x)$ in $\mathbb{K}(\alpha)[x]$.*

Proof. We only use naive algorithms. The factorization of $M[x]$ can be performed standard methods [4, 13] from a factorization algorithm in $\mathbb{K}[x]$. Addition in $\mathbb{K}(\alpha)$ costs n operations and multiplication costs $\mathcal{O}(n^2)$ operations and inversion $\mathcal{O}(n^3)$. If β is a conjugate of α, the worst case complexity of addition in $\mathbb{K}(\alpha,\beta)$ is $\mathcal{O}(n^2)$ while multiplication is $\mathcal{O}(n^4)$ and inversion $\mathcal{O}(n^6)$. If f and g are two polynomials of degree at most d, their gcd costs $\mathcal{O}(d^3n^2+n^3d^2)$ operations in $\mathbb{K}(\alpha)$ or $\mathcal{O}(d^3n^4+n^6d^2)$ if their coefficients live in $\mathbb{K}(\alpha,\beta)$. Steps $1-3$ of the algorithm cost $K+\mathcal{O}(n^2)$. Step 4 is evaluating a polynomial in $\mathbb{K}(\alpha)$, invert the result and multiply the polynomial this result. By Horner's method it is $\mathcal{O}(n^3)$. Step $5.b$ can be done in $\mathcal{O}(dmn)$ operations. For a parameter t_k doing steps $5.c-d$ is evaluating m rational functions in $\mathbb{K}(\alpha)$ and then compute $m-1$ gcd in $\mathbb{K}(\alpha,\beta)$ of degree d, this costs $\mathcal{O}(md^3n^4+mn^6d^2)$. From Theorem 6 we have to try at most $\mathcal{O}(d^2+n)$ times, so the total cost is bounded by $\mathcal{O}(md^5n^7)$.

Computing step $5.f$ is just solving a system of 3 linear equations in 4 unknowns in $\mathbb{K}(\alpha,\beta)$. This can be done in $\mathcal{O}(n^4)$ operations. Now, comparing ψ and $\psi^\sigma(u)$ in $5.e$ can be done evaluating both functions in $\mathcal{O}(d)$ parameters. Each evaluation costs $\mathcal{O}(n^6)$, so in total, this step can be done in $\mathcal{O}(mdn^6)$. Step $5.h$ we already have $m(\alpha_i,x)/m(\alpha_i,\alpha_i)$ precomputed by conjugation, so we only need to multiply the polynomials, which is dominated by computing $\mathcal{O}(n)$ products (u is always of degree ≤ 1 and we do not need to do anything with the denominator). This costs $\mathcal{O}(n^5)$. Now, instead of computing the minimal polynomial of the pole of u, we can compute its characteristic polynomial over $\mathbb{K}(\alpha)$. Since the characteristic polynomial of an $n\times n$ matrix can be done in $\mathcal{O}(n^4)$ operations and the matrix will have entries in $\mathbb{K}(\alpha)$, we can compute this characteristic polynomial in $\mathcal{O}(n^6)$ operations. Step $5.j$ can be done in $O(n^6)$ operations. Hence step 5 is bounded by $\mathcal{O}(md^5n^7)$. Since we have to perform step 5 at most n times. We get a bound of $\mathcal{O}(md^5n^8)$ operations over $\mathbb{K}$.

If $\mathcal{C}$ is not $\mathbb{K}$-definable. In step 5 we compute the automorphisms σ_i such that $\mathcal{C}=\mathcal{C}^\sigma$. From this automorphisms, we can compute the field of definition $\mathbb{L}$ in $\mathcal{O}(n^4)$ operations and repeat the whole algorithm. It is clear that the running time for the extension $\mathbb{L}\subseteq\mathbb{K}(\alpha)$ is bounded by the case $\mathbb{K}\subseteq\mathbb{K}(\alpha)$. So the global bound does not change. □

This result agrees with experimentation, the most important parameter is the degree of α over $\mathbb{K}$ and the ambient dimension of $\mathcal{C}$ tend to be not relevant in the algorithm compared to the other parameters.

Computing the hypercircle using Definition 1 is too slow, because we have to work with an ideal in n variables over $\mathbb{K}$ and make the quotient by the ideal defined by the denominator. In [8] the authors proposed a method to compute the parametrization of the hypercircle. It is based in the following result.

Theorem 15. *Let ψ be a proper parametrization of $\mathcal{C}$ with coefficients in $\mathbb{K}(\alpha)$. Let $G(x_1,\ldots,x_m):\mathcal{C}\to\mathbb{F}$ be the inverse of the parametrization. $G\in\mathbb{K}(\alpha)(x_1,\ldots,x_m)$. Write $G=\sum_{i=0}^{n-1}G_i\alpha^i$, $G_i\in\mathbb{K}(x_1,\ldots,x_m)$, $0\leq i\leq n-1$. Consider $\phi=(G_0(\psi),\ldots,G_{n-1}(\psi))$. Then $\mathcal{C}$ is defined over $\mathbb{K}$ if and only if ϕ is well defined and parametrizes a curve in $\mathbb{F}^n$. In this case ϕ is the standard* *parametrization of the associated hypercircle to ψ.*

Proof. See [8] $\square$

Algorithm 11 and the algorithm in Theorem 15 have been implemented in the Sage CAS [10], the code for the method presented in this paper can be obtained from [11]. We are interested in the average case, so we will assume that our curve is planar (since we can always make a generic projection). However, the method presented here also performs well for spatial curves. For the method based on the inverse of the parametrization of [8] we compute $(G_0, \ldots, G_{n-1})$ but we do not simplify the composition $G_i(\psi)$. This is done to avoid artifacts in the running time that appeared if we simplify the composition. The inverse of ψ is computed using the resultant method explained in [3].

We show the results for random curves of degree $2, 5, 10, 25$ and 50. First over an extension of $\mathbb{Q}$ of degree 2, over a cyclotomic extension of degree 6 and a random extension of degree 5. In all these cases $\mathcal{C}$ is defined over $\mathbb{K}$.

Case: $\alpha^2 + 1 = 0$					
method \ degree of $\mathcal{C}$	2	5	10	25	50
Moving hyperplanes:	0.08	0.15	0.27	0.87	2.58
Inverse-based method:	0.03	0.15	13.16	> 60	

Case: $\alpha^6 + \alpha^5 + \alpha^4 + \alpha^3 + \alpha^2 + \alpha + 1 = 0$					
Moving hyperplanes:	1.12	2.00	3.71	13.13	48.01
Inverse-based method:	0.13	28.61	> 60		

Case: α of degree 5, random minimal polynomial					
Moving hyperplanes:	1.04	2.01	3.84	14.28	> 60
Inverse-based method:	0.12	10.36	> 60		

Now, we show a table with a random extension of degree 5 but $\mathcal{C}$ is not defined over $\mathbb{K}$. In this case is more evident that the moving hyperplanes method is better. With high probability it will detect that the curve is not defined over $\mathbb{K}$ while trying to compute the automorphisms $u(t)$, on the other hand, the inverse-based method always has to compute the inverse of the parametrization ψ. In all cases, our algorithm computed the minimum field of definition of the corresponding curve.

Case: α of degree 5, $\mathcal{C}$ not defined over $\mathbb{K}$					
method \ degree of $\mathcal{C}$	2	5	10	25	50
Moving hyperplanes:	0.36	0.59	0.91	2.16	5.13
Inverse-based method:	0.08	12.68	> 60		

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References

[1] C. Andradas, T. Recio, and J. R. Sendra. Base field restriction techniques for parametric curves. In *Proceedings of the 1999 International Symposium on Symbolic and Algebraic Computation (Vancouver, BC)*, pages 17–22 (electronic), New York, 1999. ACM.

[2] C. Andradas, T. Recio, J. R. Sendra, and L. F. Tabera. On the simplification of the coefficients of a parametrization. *J. Symbolic Comput.*, 44(2):192–210, 2009.

[3] L. Busé and C. D'Andrea. Inversion of parameterized hypersurfaces by means of subresultants. In *ISSAC 2004*, pages 65–71. ACM, New York, 2004.

[4] H. Cohen. *A course in computational algebraic number theory*, volume 138 of *Graduate Texts in Mathematics*. Springer-Verlag, Berlin, 1993.

[5] J. Harris. *Algebraic geometry*, volume 133 of *Graduate Texts in Mathematics*. Springer-Verlag, New York, 1992. A first course.

[6] T. Recio, J. R. Sendra, L. F. Tabera, and C. Villarino. Generalizing circles over algebraic extensions. *Math. Comp.*, 79(270):1067–1089, 2010.

[7] T. Recio, J. R. Sendra, L. F. Tabera, and C. Villarino. Algorithmic detection of hypercircles. *Mathematics and Computers in Simulation*, to appear. doi:10.1016/j.matcom.2010.07.017

[8] J. R. Sendra and C. Villarino. Algebraically optimal parametrizations of quasi-polynomial algebraic curves. *J. Algebra Appl.*, 1(1):51–74, 2002.

[9] J. R. Sendra, F. Winkler, and S. Pérez-Díaz. *Rational algebraic curves: A computer algebra approach*, volume 22 of *Algorithms and Computation in Mathematics*. Springer, Berlin, 2008.

[10] W. A. Stein et al. *Sage Mathematics Software (Version 4.6.2)*. The Sage Development Team, 2011. `http://www.sagemath.org`.

[11] L. F. Tabera. Implementation of Hypercircles in the Sage CAS. 2011. `http://personales.unican.es/taberalf/hypercircles/hypercircle.html`.

[12] L. F. Tabera. Optimal affine reparametrization of rational curves. *J. Symbolic Comput.*, 46(8):967–976, 2011.

[13] B Trager. Algebraic factoring and rational function integration. *Proceedings of SYMSAC '76*, pages 219–226, 1976.