# Computing Puiseux Series for Algebraic Surfaces<sup>\*</sup>

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#### Abstract

In this paper we outline an algorithmic approach to compute Puiseux series expansions for algebraic surfaces. The series expansions originate at the intersection of the surface with as many coordinate planes as the dimension of the surface. Our approach starts with a polyhedral method to compute cones of normal vectors to the Newton polytopes of the given polynomial system that defines the surface. If as many vectors in the cone as the dimension of the surface define an initial form system that has isolated solutions, then those vectors are potential tropisms for the initial term of the Puiseux series expansion. Our preliminary methods produce exact representations for solution sets of the cyclic *n*-roots problem, for  $n = m^2$ , corresponding to a result of Backelin.

**Keywords.** algebraic surface, binomial system, cyclic *n*-roots problem, initial form, Newton polytope, orbit, permutation symmetry, polyhedral method, Puiseux series, sparse polynomial system, tropism, unimodular transformation.

## 1 Introduction

We presented polyhedral algorithms to develop Puiseux expansions, for plane curves in [2] and for space curves in [1], based on ideas described in [30]. In this paper we explain a polyhedral approach to compute series developments for algebraic surfaces. Although we use the numerical solver of PHCpack [29], one may use any solver for the leading coefficients of the series and obtain a purely symbolic method. We implemented our methods using Sage [26].

We could reduce the treatment of algebraic surfaces to the curve case by adding sufficiently many hyperplanes in general position to cut out a curve on the surface. This approach does not give enough flexibility to exploit permutation symmetry as the added general hyperplanes must ignore the symmetric structure of the polynomial system.

Although presently we do not have a fully automatic implementation suitable for benchmarking on a large class of polynomial systems, we have obtained promising results on the cyclic *n*-root systems:

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$$\begin{cases} x_0 + x_1 + \dots + x_{n-1} = 0 \\ x_0 x_1 + x_1 x_2 + \dots + x_{n-2} x_{n-1} + x_{n-1} x_0 = 0 \\ i = 3, 4, \dots, n-1 : \sum_{j=0}^{n-1} \prod_{k=j}^{j+i-1} x_k \mod n = 0 \\ x_0 x_1 x_2 \cdots x_{n-1} - 1 = 0. \end{cases}$$
(1)

The cyclic *n*-roots system is a standard benchmark problem in computer algebra, relevant to operator algebras. We refer to [28] for recent advances in the classification of complex Hadamard matrices. In [11], the close relationship of (1) with some systems occurring in optimal design of filter banks is stressed. The numerical factorization of the two dimensional surface of cyclic 9-roots into 6 irreducible cubics was reported in [23]. Recent results for the cyclic 12-roots problem can be found in [21].

Although our original intent of developing Puiseux series for algebraic sets remains, for cyclic 9-roots we found exact results: the first term of the series satisfies the entire polynomial system. These exact result correspond to known (see e.g. [3] or [11]) configurations of cyclic *n*-roots.

The type of polynomial systems targeted by the polyhedral approach are sparse polynomial systems. We introduce our approach in the next section with a very particular sparse class of systems. We use unimodular transformations to work with points at infinity. The second section ends with a general approach to solve a binomial system.

To find the initial coefficients in the Puiseux series we look for initial form systems, systems that have fewer monomials than the original systems and that are supported on faces of the Newton polytopes. Those faces of the Newton polytopes which define the initial forms are determined by their inner normals. The inner normals that define the initial form systems are the leading powers (called tropisms) of generalized Puiseux series. The leading coefficients of the series vanish at the initial form systems.

In the third section we define initial form systems, give an illustrative example, and describe the degeneration of a d-dimensional algebraic surface along a path towards the intersection with the first d coordinate planes. Polyhedral methods give us cones of pretropisms and initial form systems that may lead to initial coefficients of Puiseux series. We end this paper giving an exact description of positive dimensional sets of cyclic n-roots.

**Related work.** A geometric resolution of a polynomial system uses a parameterization of the coordinates [13] for global version of Newton's iterator [8]. Our algorithms arose from an understanding of [5, Theorem B] and are inspired by tropical methods [6] and in particular by the constructive proof of the fundamental theorem of tropical algebraic geometry [19]. Software related to [19] is Gfan [17] and the Singular library tropical.lib [18].

Connections with Gröbner bases are described in [27]. Polyhedral and tropical methods for finiteness proofs in celestial mechanics are explained in [15] and [16]. Truncations of two dimensional varieties are studied in [20]. A Newton-Puiseux algorithm for polynomials in several variables is described in [4]. The unimodular coordinate transformations are related to power transformations in [7].

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### 2 Binomial Systems

We aim to solve *sparse* polynomial systems, systems of polynomials with relatively few monomials appearing with nonzero coefficient. The sparsest polynomial systems which admit solutions with nonzero values for all coordinates consist of *exactly two* monomials in every equation and we call such systems *binomial* systems. See e.g.: [9] and [10] for more on binomial ideals.

### 2.1 An Example

Consider for example

$$\begin{cases} x_1^2 x_2 x_3^4 x_4^3 - 1 = 0\\ x_1 x_2 x_3 x_4 - 1 = 0. \end{cases}$$
(2)

We write the exponent vectors in the matrix

$$A = \begin{bmatrix} 2 & 1 & 4 & 3\\ 1 & 1 & 1 & 1 \end{bmatrix}$$
(3)

and we look for a basis of the null space of A. Two linearly independent vectors that satisfy  $A\mathbf{x} = \mathbf{0}$  are for example  $\mathbf{u} = (-3, 2, 1, 0)$  and  $\mathbf{v} = (-2, 1, 0, 1)$ . Placing  $\mathbf{u}$  and  $\mathbf{v}$  in the columns of a matrix M leads to a coordinate transformation:

$$M = \begin{bmatrix} -3 & -2 & 1 & 0 \\ 2 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad \begin{cases} x_1 = y_1^{-3} y_2^{-2} y_3 \\ x_2 = y_1^2 y_2 y_4 \\ x_3 = y_1 \\ x_4 = y_2. \end{cases}$$
(4)

The coordinate transformation  $\mathbf{x} = \mathbf{y}^M$  eliminates  $y_1$  and  $y_2$  — because  $\mathbf{u}$  and  $\mathbf{v}$  are in the null space of A — as substituting the coordinates corresponds to computing  $A\mathbf{u}$  and  $A\mathbf{v}$ , reducing the given system to

$$\begin{cases} y_3^2 y_4 - 1 = 0\\ y_3 y_4 - 1 = 0. \end{cases}$$
(5)

Solving the reduced system in (5) gives values for  $y_3$  and  $y_4$  which after substitution in the coordinate transformation in (4) yields an explicit solution for the original system in (2) with  $y_1$  and  $y_2$  as parameters.

#### 2.2 Unimodular Transformations

In the previous section we constructed in (4) a unimodular coordinate transformation  $\mathbf{x} = \mathbf{y}^M$ , where det $(M) = \pm 1$ . In the new  $\mathbf{y}$  coordinates all points that make the same inner product of the first row of the given exponent matrix A will have the same value for  $y_1$ .

We are given a matrix  $B \in \mathbb{Z}^{k \times n}$ , k < n and assume moreover that the rank of A equals k. The Smith normal form of B consists of the triplet (U, S, V), with  $U \in \mathbb{Z}^{k \times k}$ ,  $S \in \mathbb{Z}^{k \times n}$ ,  $V \in \mathbb{Z}^{n \times n}$ , with  $\det(U) = \pm 1$ ,  $\det(V) = \pm 1$ , the only nonzero elements of S are on the diagonal and UBV = S. Because the rank of A equals k, the rank of S is also k.

If U equals the identity matrix, then UBV = S implies  $B = SV^{-1}$ . This means that for any  $\mathbf{x}$ , the outcome of  $B\mathbf{x}$  is the same as  $SV^{-1}\mathbf{x}$ . Using  $V^{-1}$  to define the unimodular transformation will

create fractional exponents in case the elements on the diagonal of S are strictly larger than one, but those fractions can occur only for the first k variables. Note that the first k variables appear with the same power after the unimodular coordinate transformation so they can be removed.

For the matrix A in (3), the matrix B has in its two rows the vectors **u** and **v** so that  $AB^T = \mathbf{0}$ :

$$B = \begin{bmatrix} -3 & 2 & 1 & 0 \\ -2 & 1 & 0 & 1 \end{bmatrix}.$$
 (6)

The computation of the Smith normal form of B with GAP [14] (from the console in Sage [26]) gives

$$U = \begin{bmatrix} 1 & -2 \\ 2 & -3 \end{bmatrix}, \quad S = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},$$
(7)

and

$$V = \begin{bmatrix} 1 & 0 & 1 & -2 \\ 0 & 1 & 2 & -3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$
 (8)

We use the inverses  $U^{-1}$  and  $V^{-1}$  to construct a unimodular transformation extending  $U^{-1}$  with the identity matrix, as follows:

$$\begin{bmatrix} -3 & 2 & 0 & 0 \\ -2 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 1 & -2 \\ 0 & 1 & 2 & -3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
(9)

and this product gives the transpose of M, the matrix in the unimodular transformation of (4). This examples illustrates the case when U is not the identity matrix and where we may ignore S as its diagonal elements are all equal to one.

We point out that the vectors in the null space of the exponent matrix A as in (3) are typically normalized so that the greatest common divisors of the components of the vectors equals one. We may change coordinates so that the first vector in the null space has only its first coordinate different from zero, the second vector in the null space can have nonzero entries only in the first two coordinates, etc. For a 2-dimensional surface in  $\mathbb{C}^5$ , consider for example the null space could be spanned by the rows in the matrix

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 2 & 0 & 0 & 0 \\ 3 & 5 & 7 & 0 & 0 \end{bmatrix}.$$
 (10)

As the rows of B belong to the null space of a matrix (in particular they span a 3-dimensional cone), we may multiply the row independently with different factors, e.g.:

$$\bar{B} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 5 & 10 & 0 & 0 & 0 \\ 6 & 10 & 14 & 0 & 0 \end{bmatrix}.$$
 (11)

In general we multiply the rows so that each column is divisible by the number on the diagonal. Then we may scale the columns to obtain ones on each diagonal:

$$\widehat{\bar{B}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 5 & 1 & 0 & 0 & 0 \\ 6 & 1 & 1 & 0 & 0 \end{bmatrix}.$$
(12)

At the monomial level, this division by 10 in the second column corresponds to replacing  $x_2$  by  $x_2^{10}$  in the system. Because  $x_2$  will cancel out in the reduced system, this variable substitution concerns only the parametrization of the surface and has no effect on the resulting binomial system. For a lower triangular matrix with ones on its diagonal, the Smith normal form S has also ones on its diagonal.

### 2.3 Solving Binomial Systems

We denote a binomial system by  $\mathbf{x}^A - \mathbf{c} = \mathbf{0}$ , where  $A \in \mathbb{Z}^{k \times n}$  and  $\mathbf{c} = (c_1, c_2, \ldots, c_k)$  with  $c_i \neq 0$  for all  $i = 1, 2, \ldots, k$ . If the rank of A equals k, then k is the codimension of the solution set. Given the tuple  $(A, \mathbf{c})$ , the solution set of  $\mathbf{x}^A - \mathbf{c} = \mathbf{0}$  is described by a unimodular transformation M and a set of values for the last n - k variables. Eventually, following the end of the previous section, the coordinate transformation may involve a relabeling of variables and a scaling of the exponents.

In the sketch of the solution method below we assume that A has rank k, otherwise  $\mathbf{x}^A - \mathbf{c} = \mathbf{0}$  has no (n - k)-dimensional solution set for general values of **c**. The steps are as follows:

- 1. Compute the null space B of A, d = n k.
- 2. Compute the Smith normal form (U, S, V) of B.
- 3. Depending on U and S do one of the following:
  - If U is the identity matrix, then  $M = V^{-1}$  and the first d variables have positive denominators in their powers when not all elements on the diagonal of S are equal to one.
  - If U is not the identity matrix and if all elements on the diagonal of S are one, then extend  $U^{-1}$  with an identity matrix to obtain an *n*-by-*n* matrix E that has  $U^{-1}$  in its first d rows and columns. Then,  $M = EV^{-1}$ .
  - In all other cases, change coordinates so the null space *B* has a triangular shape with ones on the diagonal. Then, with the new *B*, return to step 2.
- 4. After the coordinate transformation  $\mathbf{x} = \mathbf{y}^M$ , compute the leading coefficients solving a binomial system of k equations in k unknowns. Return M and the corresponding solutions of the binomial system.

# 3 Sparse Polynomial Systems

To look for *d*-dimensional components of sparse polynomial systems, we investigate solutions of initial forms defined by cones of normal vectors. In order for the initial form systems to have solutions with all coordinates different from zero, they need to be at least binomial systems.

#### 3.1 Initial Forms

A polynomial f in n variables  $\mathbf{x} = (x_1, x_2, \dots, x_n)$  is denoted as

$$f(\mathbf{x}) = \sum_{\mathbf{a} \in A} c_{\mathbf{a}} \mathbf{x}^{\mathbf{a}}, \quad c_{\mathbf{a}} \in \mathbb{C} \setminus \{0\},$$
(13)

 $x^{\mathbf{a}} = x_1^{a_1} x_2^{a_2} \cdots x_n^{a_n}$ , where A is the set of all exponents of monomials with nonzero coefficient. The set A is the *support* of f and the convex hull of A is the *Newton polytope* P of f. Any nonzero vector  $\mathbf{v}$  defines a face of P, spanned by

$$\operatorname{in}_{\mathbf{v}}(A) = \{ \mathbf{b} \in A \mid \langle \mathbf{b}, \mathbf{v} \rangle = \min_{\mathbf{a} \in A} \langle \mathbf{a}, \mathbf{v} \rangle \},$$
(14)

where  $\langle \cdot, \cdot \rangle$  denotes the usual inner product of two vectors. We use the notation  $in_{\mathbf{v}}(A)$  because a face of a support set defines an *initial form* of the polynomial f:

$$\operatorname{in}_{\mathbf{v}}(f)(\mathbf{x}) = \sum_{\mathbf{a} \in \operatorname{in}_{\mathbf{v}}(A)} c_{\mathbf{a}} \mathbf{x}^{\mathbf{a}},\tag{15}$$

where A is the support of f. For a system  $f(\mathbf{x}) = \mathbf{0}$  and a nonzero vector  $\mathbf{v}$ , the *initial form* system  $\operatorname{in}_{\mathbf{v}}(f)(\mathbf{x}) = \mathbf{0}$  is defined by the initial forms of the polynomials in f with respect to  $\mathbf{v}$ .

Because the initial coefficients of Puiseux series expansions are solutions to initial form systems, the initial forms we consider must have at least two monomials, otherwise the solutions will have coordinates equal to zero and are unfit as leading coefficients in a Puiseux series development.

#### 3.2 An Illustrative Example

In this section we indicate how the presence of a higher dimensional solution set manifests itself from the relative position of the Newton polytopes of the polynomials in the system. To illustrate a numerical irreducible decomposition of the solution set of a polynomial system, the following system was used in [22]:

$$f(x_1, x_2, x_3) = \begin{cases} (x_2 - x_1^2)(x_1^2 + x_2^2 + x_3^2 - 1)(x_1 - 0.5) = 0\\ (x_3 - x_1^3)(x_1^2 + x_2^2 + x_3^2 - 1)(x_2 - 0.5) = 0\\ (x_2 - x_1^2)(x_3 - x_1^3)(x_1^2 + x_2^2 + x_3^2 - 1)(x_3 - 0.5) = 0 \end{cases}$$
(16)

The solution set  $Z = f^{-1}(\mathbf{0})$  is decomposed as

$$Z = Z_2 \cup Z_1 \cup Z_0 \tag{17}$$

$$= \{Z_{21}\} \cup \{Z_{11} \cup Z_{12} \cup Z_{13} \cup Z_{14}\} \cup \{Z_{01}\}$$
(18)

where

- 1.  $Z_{21}$  is the sphere  $x_1^2 + x_2^2 + x_3^2 1 = 0$ ,
- 2.  $Z_{11}$  is the line  $(x_1 = 0.5, x_3 = 0.5^3)$ ,
- 3.  $Z_{12}$  is the line  $(x_1 = \sqrt{0.5}, x_2 = 0.5),$

4.  $Z_{13}$  is the line  $(x_1 = -\sqrt{0.5}, x_2 = 0.5),$ 5.  $Z_{14}$  is the twisted cubic  $(x_2 - x_1^2 = 0, x_3 - x_1^3 = 0),$ 6.  $Z_{01}$  is the point  $(x_1 = 0.5, x_2 = 0.5, x_3 = 0.5).$ 

A first cascade of homotopies in [22] needed 197 solution paths to compute generic points on all components. The equation-by-equation solver of [25] reduced the number of paths down to 13. The Newton polytopes of the polynomials in the system are displayed in Figures 1 and 2.

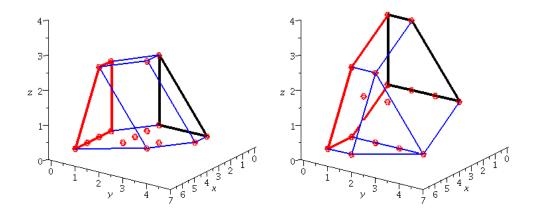


Figure 1: From top to bottom, we see the Newton polytopes of  $f_1$ ,  $f_2$ , and  $f_3$  of the polynomials in (16). The edges of the faces of the polytopes with normals (1, 0, 0) and (0, 1, 0) are marked in bold, respectively in red and black.

Consider a point on the 2-dimensional solution component of  $f^{-1}(\mathbf{0})$  and let the first coordinate of that point go to zero. As  $x_1 = t \to 0$ :

$$\begin{aligned}
&\operatorname{in}_{(1,0,0)}(f)(x_1, x_2, x_3) \\
&= \begin{cases} x_2(x_2^2 + x_3^2 - 1)(-0.5) = 0 \\ x_3(x_2^2 + x_3^2 - 1)(x_2 - 0.5) = 0 \\ x_2x_3(x_2^2 + x_3^2 - 1)(x_3 - 0.5) = 0. \end{aligned}$$
(19)

Alternatively, as  $x_2 = s \rightarrow 0$ , we end up at a solution of the initial form system:

$$\begin{aligned}
& \text{in}_{(0,1,0)}(f)(x_1, x_2, x_3) \\
&= \begin{cases} -x_1^2(x_1^2 + x_3^2 - 1)(x_1 - 0.5) = 0 \\ (x_3 - x_1^3)(x_1^2 + x_3^2 - 1)(-0.5) = 0 \\ -x_1^2(x_3 - x_1^3)(x_1^2 + x_3^2 - 1)(x_3 - 0.5) = 0. \end{aligned}$$
(20)

Looking at the Newton polytopes along  $\mathbf{v} = (1,0,0)$  and  $\mathbf{v} = (0,1,0)$ , we consider faces of the Newton polytopes, see Figures 1 and 2.

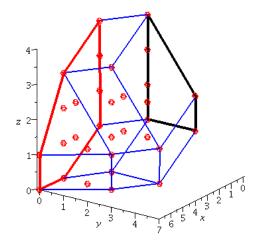


Figure 2: The Newton polytopes of the third polynomial in (16). The edges of the faces of the polytopes with normals (1,0,0) and (0,1,0) are marked in bold, respectively in red and black.

Combining the two degenerations, we arrive at the initial form system:

$$\begin{aligned}
& \text{in}_{(0,1,0)}(\text{in}_{(1,0,0)}(f))(x_1, x_2, x_3) \\
&= \begin{cases} x_2(x_3^2 - 1)(-0.5) \\ x_3(x_3^2 - 1)(-0.5) \\ x_2x_3(x_3^2 - 1)(x_3 - 0.5) \end{aligned}$$
(21)

The factor  $x_3^2 - 1$  is shared with  $in_{(1,0,0)}(in_{(0,1,0)}f)(x_1, x_2, x_3)$ .

Based on these degenerations, we arrive at the following representation for a solution surface. The sphere is two dimensional,  $x_1$  and  $x_2$  are free:

$$\begin{cases} x_1 = t_1 \\ x_2 = t_2 \\ x_3 = 1 + c_1 t_1^2 + c_2 t_2^2. \end{cases}$$
(22)

For  $t_1 = 0$  and  $t_2 = 0$ ,  $x_3 = 1$  is a solution of  $x^3 - 1 = 0$ . Substituting  $(x_1 = t_1, x_2 = t_2, x_3 = 1 + c_1t_1^2 + c_2t_2^2)$  into the original system gives linear conditions on the coefficients of the second term:  $c_1 = -0.5$  and  $c_2 = -0.5$ .

#### 3.3 Asymptotics of Algebraic Surfaces and Puiseux Series

Denoting by d the dimension of the algebraic surface defined by  $f(\mathbf{x}) = \mathbf{0}$ , for  $\mathbf{x} \in \mathbb{C}^n$ , we assume the defining equations are in Noether position so we may specialize the first d coordinates to random complex numbers in  $f(\mathbf{x}) = \mathbf{0}$  and obtain a system with isolated solutions. Moreover, we assume that when specializing the first d variables to zero, the algebraic set remains of dimension d. Geometrically this means that we assume that the algebraic set meets the first d coordinate planes (perpendicular to the first d coordinate axes) properly. We consider what happens when starting at a random point on the surface we move the first d coordinates to zero. For simplicity of notation we take d = 2 and consider a multiparameter family of polynomial systems:

$$\begin{cases} f(\mathbf{x}) &= \mathbf{0} \\ x_1 &= c_1 t_1 \\ x_2 &= c_2 t_1^{v_{1,2}} t_2^{v_{2,2}} (c_{1,2} + O(t_1, t_2)), \end{cases}$$
(23)

with  $c_1, c_2, c_{1,2} \in \mathbb{C} \setminus \{0\}$ ,  $v_{1,1}, v_{1,2} \in \mathbb{Q}$ , letting  $t_1$  and  $t_2$  go from 1 to 0, starting at a generic point on the surface with its first two coordinates equal to  $c_1$  and  $c_2$ .

The multiparameter family in (23) specifies the last equation as a series to leave enough freedom for the actual shape of the surface. While we may always move  $x_1$  as going linearly to zero, with  $x_1 = c_1 t_1$ , the second coordinate of a point along a path on the surface may no longer move linearly. Taking  $x_2$  as  $c_2 t_2$  would be too restrictive.

As we move  $x_1$  to zero as  $t_1$  goes to zero, then  $x_2$  can go to zero as well if  $v_{1,1} > 0$  and  $v_{2,2} > 0$ , or go to infinity if  $v_{1,2} < 0$  or  $v_{2,2} < 0$ , or go to  $c_2c_{1,2}$  if both  $v_{1,2} = 0$  and  $v_{2,2} = 0$ . The multiparameter family in (23) contains what we imagine as a multiparameter version of a Puiseux series for algebraic curves. Similar to  $x_2$ , the other components of the moving point can be developed as a generalized Puiseux series

$$x_k = c_k t_1^{v_{1,k}} t_2^{v_{2,k}} (c_{1,k} + O(t_1, t_2)),$$
(24)

 $c_k, c_{k,2} \in \mathbb{C} \setminus \{0\}, v_{k,1}, v_{k,2} \in \mathbb{Q}$ . If in the limit – when  $t_1$  and  $t_2$  are both zero – the solution is finite and of multiplicity one, then the generalized Puiseux series coincides with a multivariate Taylor series.

As  $t_1$  and  $t_2$  go to zero, the system  $f(t_1, t_2) = \mathbf{0}$  — obtained after replacing  $x_1$  and  $x_2$  using the last two equations of (23) and after substituting (24) for the remaining n-2 into  $f(\mathbf{x}) = \mathbf{0}$  must have at least two monomials with lowest power in  $t_1$  and lowest power in  $t_2$  in every equation because  $c_k, c_{1,k} \in \mathbb{C} \setminus \{0\}$  for all k = 1, 2, ..., n. We call the part of  $f(\mathbf{x}) = \mathbf{0}$  corresponding to  $f(t_1, t_2)$  with lowest powers of  $t_1$  and  $t_2$  the initial form system of  $f(\mathbf{x}) = \mathbf{0}$  with respect to the normal vectors  $\mathbf{v}_1 = (1, v_{1,2}, v_{1,3}, ..., v_{1,n})$  and  $\mathbf{v}_2 = (0, v_{2,2}, v_{2,3}, ..., v_{2,n})$ . Because the normal vectors are the leading powers of the generalized Puiseux series,  $\mathbf{v}_1$  and  $\mathbf{v}_2$  can be called *tropisms* in analogy to the case of algebraic curves.

Given any vector  $\mathbf{v} \in \mathbb{Q}^n$ ,  $\mathbf{v} \neq \mathbf{0}$ , the initial form system is denoted as  $\operatorname{in}_{\mathbf{v}}(f)(\mathbf{x}) = \mathbf{0}$ . Every monomial  $\mathbf{x}^{\mathbf{a}}$  in  $\operatorname{in}_{\mathbf{v}}(f)$  makes a minimal inner product  $\langle \mathbf{a}, \mathbf{v} \rangle$ , minimal with respect to any other monomial in  $f \setminus \operatorname{in}_{\mathbf{v}}(f)$ , i.e.:  $\langle \mathbf{a}, \mathbf{v} \rangle \in \langle \mathbf{b}, \mathbf{v} \rangle$  for all  $\mathbf{x}^{\mathbf{b}} \in f \setminus \operatorname{in}_{\mathbf{v}}(f)$ . For a 2-dimensional surface with tropisms  $\mathbf{v}_1$  and  $\mathbf{v}_2$  solutions to the the initial form system  $\operatorname{in}_{\mathbf{v}_1}(\operatorname{in}_{\mathbf{v}_2}(f))(\mathbf{x}) = \mathbf{0}$  are the leading coefficients of the generalized Puiseux series.

The derivation for an algebraic surface in any dimension d is straightforward and we have the following:

**Proposition 3.1** If  $f(\mathbf{x}) = \mathbf{0}$  is in Noether position and defines an algebraic surface of dimension d in  $\mathbb{C}^n$ , then there are d linearly independent tropisms  $\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_d \in \mathbb{Q}^n$  so that the initial form system  $\operatorname{in}_{\mathbf{v}_1}(\operatorname{in}_{\mathbf{v}_2}(\cdots \operatorname{in}_{\mathbf{v}_d}(f)\cdots))(\mathbf{x}) = \mathbf{0}$  has a solution  $\mathbf{c} \in (\mathbb{C} \setminus \{0\})^n$ . This solution and the tropisms are the leading coefficients and powers of a generalized Puiseux series expansion for the algebraic surface.

#### 3.4 Polyhedral Methods

In our algorithm to develop Puiseux series developments for algebraic surfaces, Proposition 3.1 is applied as follows. If we are looking for a surface of dimension d and

- if there are no cones of vectors perpendicular to edges of the Newton polytopes of  $f(\mathbf{x}) = \mathbf{0}$  of dimension d, then there the system  $f(\mathbf{x}) = \mathbf{0}$  has no solution surface of dimension d that intersects the first d coordinate planes properly; otherwise
- if a *d*-dimensional cone of vectors perpendicular to edges of the Newton polytopes exists, then that cone defines a part of the tropical prevariety.

We call a vector perpendicular to at least one edge of every Newton polytope of  $f(\mathbf{x}) = \mathbf{0}$  a candidate tropism or *pretropism*.

Algorithms to compute a tropical prevariety are described in [6]. As we outlined in [1], we applied cddlib [12] to the Cayley embedding of the Newton polytopes of the system to compute pretropisms. With the Cayley embedding we managed to compute all pretropisms of the cyclic 12-roots problem, reported in [1].

For highly structured problems such as the cyclic *n*-roots problem, a tropism found at lower dimension often occurs also in extended form for higher dimensions. For example, for n = 4, a tropism is (+1, -1, +1, -1) which extends directly to (+1, -1, +1, -1, +1, -1) for n = 8 and (+1, -1, +1, -1, +1, -1, +1, -1, +1, -1, +1, -1) for n = 12, and any *n* that is a multiple of 4.

In addition to the extraneous results reported from the Cayley embedding, it suffices to restrict to pretropisms with positive first coordinate because geometrically we intersect the surface with the coordinate hyperplane perpendicular to the  $x_1$ -axes at the end of moving  $x_1$  to zero. Allowing a negative first exponent in the first pretropism corresponds to intersecting the surface at infinity, when in the limit we let  $x_1$  go to infinity.

In any case, after the computation of pretropisms, exploiting permutation symmetry is relatively straightforward as we can group the pretropisms in orbits and process only one generator per orbit.

#### 3.5 Puiseux Series for Algebraic Surfaces

The approach to develop Puiseux series proceed as follows. For every d-dimensional cone C of pretropisms:

- 1. we select d linearly independent generators to form the d-by-n matrix A and the corresponding unimodular transformation  $\mathbf{x} = \mathbf{y}^M$ .
- 2. Because the matrix A contain pretropisms, the initial form system  $\operatorname{in}_{\mathbf{v}_1}(\operatorname{in}_{\mathbf{v}_2}(\cdots \operatorname{in}_{\mathbf{v}_d}(f)\cdots))(\mathbf{x}) = \mathbf{0}$  determined by the rows  $\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_d$  of A has at least two monomials in every equation. If the initial form system has no solution with all coordinates different from zero, then we move to the next cone C and return to step 1, else we continue with the next step.
- 3. Solutions of the initial form system found in the previous step are leading coefficients in a potential Puiseux series with corresponding leading powers equal to the pretropisms. If the leading term satisfies the entire polynomial system, then we report an explicit solution of

the system and we continue processing the next cone C. Otherwise, we take the current leading term to the next step.

4. If there is a second term in the Puiseux series, then we have computed an initial development for an algebraic surface and report this development in the output.

To compute in the last step a second term in a multivariate Puiseux series seems very complicated, but we point out that it is not necessary to compute the second term in full generality. To ensure that a solution of an initial form system is not isolated, it suffices that we can compute a series development for a curve starting at that solution. In practice this means that we may restrict all but one free variable in the series development and apply the methods we outlined in [1] for the computation of the second term of the Puiseux series for a space curve.

# 4 Applications

With our polyhedral approach we are able to recover exact representations for positive solutions of the cyclic *n*-roots problem.

### 4.1 On cyclic 9-roots

Taking n = 9 in (1), for cyclic 9-roots, we show that our solution can be transformed into the same format as in the proof we found in [11, Lemma 1.1] of the statement in [3] that square divisors of n lead to infinitely many cyclic n-roots.

Among the tropisms computed by cddlib [12] on the Cayley embedding of the Newton polytopes of the system, there is a two dimensional cone of normal vectors spanned by  $\mathbf{u} = (1, 1, -2, 1, 1, -2, 1, 1, -2)$  and  $\mathbf{v} = (0, 1, -1, 0, 1, -1, 0, 1, -1)$ . The vectors  $\mathbf{u}$  and  $\mathbf{v}$  are tropisms. The initial form system in<sub>**u**</sub>(in<sub>**v**</sub>(f))( $\mathbf{x}$ ) = **0** is

Observe that, compared to the original system, the number of monomials is reduced significantly and is thus sparser and easier to solve than the original system. To solve the initial form system, we eliminate  $x_0$  and  $x_1$  with a unimodular coordinate transformation M that has **u** and **v** on its first two rows. The last seven rows of M are zero except for the ones on the diagonal:

$$M = \begin{bmatrix} 1 & 1 & -2 & 1 & 1 & -2 & 1 & 1 & -2 \\ 0 & 1 & -1 & 0 & 1 & -1 & 0 & 1 & -1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

$$(26)$$

The matrix M defines the unimodular coordinate transformation  $\mathbf{x} = \mathbf{y}^M$ :

$$\begin{aligned} x_0 &= y_0 & x_3 = y_0 y_3 & x_6 = y_0 y_6 \\ x_1 &= y_0 y_1 & x_4 = y_0 y_1 y_4 & x_7 = y_0 y_1 y_7 \\ x_2 &= y_0^{-2} y_1^{-1} y_2, & x_5 = y_0^{-2} y_1^{-1} y_5, & x_8 = y_0^{-2} y_1^{-1} y_8. \end{aligned}$$

$$(27)$$

The transformation  $\mathbf{x} = \mathbf{y}^M$  reduces the initial form system  $\operatorname{in}_{\mathbf{u}}(\operatorname{in}_{\mathbf{v}}(f))(\mathbf{x} = \mathbf{y}^M) = \mathbf{0}$  to a system of 9 equations in 7 unknowns.

After adding two slack variables to square the system (see [24] for an illustration of introducing slack variables), the mixed volume equals 326. In contrast, the mixed volume of the original polynomial system equals 20,376.

For this problem it turns out that the entire cyclic 9-roots system vanishes at this first term of the series expansion. Recognizing the numerical roots as primitive roots of unity leads to an exact representation of the two dimension set of cyclic 9-roots.

Denoting by  $u = e^{i2\pi/3}$  the primitive third root of unity,  $u^3 - 1 = 0$ , our representation of the solution set is

$$\begin{aligned}
x_0 &= t_1 & x_3 = t_1 u & x_6 = t_1 u^2 \\
x_1 &= t_1 t_2 & x_4 = t_1 t_2 u & x_7 = t_1 t_2 u^2 \\
x_2 &= t_1^{-2} t_2^{-1} u^2 & x_5 = t_1^{-2} t_2^{-1} & x_8 = t_1^{-2} t_2^{-1} u.
\end{aligned} \tag{28}$$

Introducing new variables  $y_0 = t_1$ ,  $y_1 = t_1 t_2$ , and  $y_2 = t_1^{-2} t_2^{-1} u^2$ , our representation becomes

$$\begin{array}{ll} x_0 = y_0 & x_3 = y_0 u & x_6 = y_0 u^2 \\ x_1 = y_1 & x_4 = y_1 u & x_7 = y_1 u^2 \\ x_2 = y_2 & x_5 = y_2 u & x_8 = y_2 u^2 \end{array}$$
 (29)

which modulo  $y_0^3 y_1^3 y_2^3 u^9 - 1 = 0$  satisfies by plain substitution the cyclic 9-roots system, as in the proof of [11, Lemma 1.1].

Note that the representation in (28) allows a quick computation of the degree of the surface. This degree equals the number of points in the intersection of the surface with two random hyperplanes. Using (28) for points on the surface, the two random hyperplanes become a system in the monomials  $t_1$ ,  $t_1t_2$ , and  $t_1^{-2}t_2^{-1}$ :

$$\begin{cases} \alpha_1 t_1 + \alpha_{1,2} t_1 t_2 + \alpha_{-2,-1} t_1^{-2} t_2^{-1} = 0\\ \beta_1 t_1 + \beta_{1,2} t_1 t_2 + \beta_{-2,-1} t_1^{-2} t_2^{-1} = 0 \end{cases}$$
(30)

for some complex numbers  $\alpha_{i,j}$  and  $\beta_{i,j}$ . The above system is equivalent to the system

$$\begin{cases} t_1^{-3}t_2^{-1} - c_1 = 0\\ t_2 - c_2 = 0 \end{cases}$$
(31)

for some  $c_1, c_2 \in \mathbb{C}$ . We see that for any nonzero  $c_1$  and  $c_2$ , the system has three solutions. So the algebraic surface represented in (28) is a cubic surface. Using other roots of unity and permuting variables leads to an entire orbit of cubic surfaces.

### 4.2 On cyclic $m^2$ -roots

While the Cayley embedding becomes too wasteful to extend the computation of *all* candidate tropisms beyond n = 12, by the structure of the tropisms for n = 9 we can predict the tropisms for cyclic 16-roots:

$$\mathbf{u} = (1, 1, 1, -3, 1, 1, 1, -3, 1, 1, 1, -3, 1, 1, 1, -3), 
\mathbf{v} = (0, 1, 1, -2, 0, 1, 1, -2, 0, 1, 1, -2, 0, 1, 1, -2), 
\mathbf{w} = (0, 0, 1, -1, 0, 0, 1, -1, 0, 0, 1, -1, 0, 0, 1, -1),$$
(32)

and the corresponding initial form solutions are primitive fourth roots of unity. Similar to (28) and (29) we can show that the exact representation obtained with tropical methods corresponds to what is in the proof of [11, Lemma 1.1].

A general pattern for surfaces of cyclic  $m^2$ -roots is in the following proposition.

**Proposition 4.1** For  $n = m^2$ , there is an (m-1)-dimensional set of cyclic n-roots, represented exactly as

$$\begin{aligned}
x_{km+0} &= u_k t_0 \\
x_{km+1} &= u_k t_0 t_1 \\
x_{km+2} &= u_k t_0 t_1 t_2 \\
\vdots \\
x_{km+m-2} &= u_k t_0 t_1 t_2 \cdots t_{m-2} \\
x_{km+m-1} &= u_k t_0^{-m+1} t_1^{-m+2} \cdots t_{m-3}^{-2} t_{m-2}^{-1} \\
\end{aligned}$$
(33)

for k = 0, 1, 2, ..., m - 1 and  $u_k = e^{i2k\pi/m}$ .

In addition to the triplet of tropisms  $(\mathbf{u}, \mathbf{v}, \mathbf{w})$ , we found other components, not strictly along the general pattern:

$$\begin{array}{rcl} x_{0} &= t_{0} & x_{0} &= t_{0} \\ x_{1} &= t_{0}^{-1}t_{1}t_{2} & x_{1} &= t_{0}^{-1}t_{1}t_{2} \\ x_{2} &= t_{0}t_{2} & x_{2} &= t_{0}t_{2} \\ x_{3} &= It_{0}^{-1}t_{1}^{-1}t_{2}^{-2} & x_{3} &= -It_{0}^{-1}t_{1}^{-1}t_{2}^{-2} \\ x_{4} &= -t_{0} & x_{4} &= -t_{0} \\ x_{5} &= (-1/I)t_{0}^{-1}t_{1}t_{2} & x_{5} &= (1/I)t_{0}^{-1}t_{1}t_{2} \\ x_{6} &= -t_{0}t_{2} & x_{6} &= -t_{0}t_{2} \\ x_{7} &= t_{0}^{-1}t_{1}^{-1}t_{2}^{-2} & x_{7} &= t_{0}^{-1}t_{1}^{-1}t_{2}^{-2} \\ x_{8} &= t_{0} & x_{8} &= t_{0} \\ x_{9} &= -t_{0}^{-1}t_{1}t_{2} & x_{9} &= -t_{0}^{-1}t_{1}t_{2} \\ x_{10} &= t_{0}t_{2} & x_{10} &= t_{0}t_{2} \\ x_{11} &= -It_{0}^{-1}t_{1}^{-1}t_{2}^{-2} & x_{11} &= It_{0}^{-1}t_{1}t_{2}^{-2} \\ x_{13} &= (1/I)t_{0}^{-1}t_{1}t_{2} & x_{13} &= (-1/I)t_{0}^{-1}t_{1}t_{2} \\ x_{14} &= -t_{0}t_{2} & x_{14} &= -t_{0}t_{2} \\ x_{15} &= -t_{0}^{-1}t_{1}^{-1}t_{2}^{-2} & x_{15} &= -1t_{0}^{-1}t_{1}^{-1}t_{2}^{-2} \end{array}$$

where  $I = \sqrt{-1}$ .

# 5 Conclusions

Preliminary experiments with a polyhedral method for algebraic surfaces has given promising results for an important benchmark for polynomial system solving, the cyclic n-roots problem. The approach is well suited to exploit permutation symmetries.

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