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Computing effectively stabilizing controllers for a class of nD systems

Yacine Bouzidi * Thomas Cluzeau ** Guillaume Moroz *** Alban Quadrat *

* INRIA Lille-Nord Europe, Lille, France (e-mail: {yacine.bouzidi,alban.quadrat}@inria.fr).
** University of Limoges ; CNRS ; XLIM UMR 7252, Limoges, France (e-mail: thomas.cluzeau@unilim.fr).
*** INRIA Nancy-Grand Est, Nancy, France (e-mail: guillaume.moroz@inria.fr)

Abstract:
In this paper, we study the internal stabilizability and internal stabilization problems for multidimensional (nD) systems. Within the fractional representation approach, a multidimensional system can be studied by means of matrices with entries in the integral domain of structurally stable rational fractions, namely the ring of rational functions in an integral domain $D$. A left factorization of $P_1(z) = \cdots = P_r(z) = 0$ is defined by: $A^{1/x(q+r)}R = \{ \lambda \in A^{1/x(q+r)} | \exists \alpha \in A \setminus \{0\} : a \lambda \in A^{1/x(q)q} R \}$. This projectivity condition is in turn equivalent to the fact that the reduced minors of the matrix $R$ do not have common zeros in $\mathbb{C}^n$ (see also Lin (1998)). In other terms, if we denote by $p_1, \ldots, p_r$ the reduced minors of $R$, i.e., the $q \times q$ minors of $R$ divided by their gcd, by $I = (p_1, \ldots, p_r)$ the polynomial ideal generated by the $p_i$’s, and by $V(I) = \{ z \in \mathbb{C}^n | p_1(z) = \cdots = p_r(z) = 0 \}$ the associated algebraic variety, then the system is internally stabilizable if and only if $V(I) \cap \mathbb{C}^n = \emptyset$.

1. INTRODUCTION

Multidimensional or nD systems (Bose (1984)) are systems of functional equations whose unknown functions depend on $n$ independent variables. The stabilizability and stabilization problems are fundamental issues in the study of multidimensional systems in control theory. Nowadays, the problem is well-understood in the case of 1D systems whereas progress for nD systems with $n \geq 2$ are rather slow. One approach for handling stabilizability or stabilization issues in systems theory is the fractional representation approach (Vidyasagar (2011)) in which a plant is represented by its transfer matrix $P \in K^{q \times r}$ where $K = \mathbb{R}(z_1, \ldots, z_n)$. This transfer matrix admits a left factorization $P = D^{-1}N$ (also called fractional representation of $P$), where the matrices $D \in A^{q \times q}$ satisfying $\det(D) \neq 0$ and $N \in A^{q \times r}$ have entries in the integral domain $A = \mathbb{R}(z_1, \ldots, z_n)$ of structurally stable rational fractions, namely the ring of rational functions in $z_1, \ldots, z_n$ which have no poles in the closed unit polydisc of $\mathbb{C}^n$ defined by:

$$\mathbb{U}^n = \{ z = (z_1, \ldots, z_n) \in \mathbb{C}^n | |z_1| \leq 1, \ldots, |z_n| \leq 1 \}. $$

Introducing the matrix $R = (D - N) \in A^{q \times (q+r)}$, it is known (see Quadrat (2003b,a)) that the multidimensional system given by the transfer matrix $P = D^{-1}N$ is then internally stabilizable if and only if the $A$-module $A^{1/x(q+r)}/A^{1/x(q+r)}R$ is a projective $A$-module of rank $r$, where the closure $\overline{A^{1/x(q+r)}R}$ of $A^{1/x(q+r)}R$ in $A^{1/x(q+r)}$ is defined by:

$$\overline{A^{1/x(q+r)}R} = \{ \lambda \in A^{1/x(q+r)} | \exists \alpha \in A \setminus \{0\} : a \lambda \in A^{1/x(q)q} R \}. $$

This projectivity condition is equivalent to the fact that the reduced minors of the matrix $R$ do not have common zeros in $\mathbb{C}^n$ (see also Lin (1998)). In other terms, if we denote by $p_1, \ldots, p_r$ the reduced minors of $R$, i.e., the $q \times q$ minors of $R$ divided by their gcd, by $I = (p_1, \ldots, p_r)$ the polynomial ideal generated by the $p_i$’s, and by $V(I) = \{ z \in \mathbb{C}^n | p_1(z) = \cdots = p_r(z) = 0 \}$ the associated algebraic variety, then the system is internally stabilizable if and only if $V(I) \cap \mathbb{C}^n = \emptyset$.

The first contribution of the present paper is to provide an effective algorithm for testing the stabilizability condition $V(I) \cap \mathbb{C}^n = \emptyset$ for the class of nD systems for which the ideal $I$ is zero-dimensional, i.e., the $p_i$’s have only a finite number of common complex zeros (i.e., $V(I)$ consists of a finite number of complex points). Note that this class includes the class of 2D systems. Our main idea is to take advantage of the univariate representation technique proposed by Lin (1998) for stabilizability testing for 2D systems.

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for zero-dimensional ideals (Canny (1988); Becker and Wörmann (1996); Alonso et al. (1996); Rouillier (1999)). This concept, which can be traced back to Kronecker (1882), yields a one-to-one correspondence between the elements of \( V(I) \) and the zeros of a univariate polynomial \( f \). Numerical techniques can thus be applied to compute certified numerical approximations of the roots of \( f \) and then of those of \( V(I) \).

In the case of a stabilizable plant, the next step consists in computing a stabilizing controller which can be achieved by computing a stable (i.e., devoid from zeros in \( \mathbb{C}^n \)) polynomial \( s \in I \) (see Lin (1988)). The polydisc Nullstellensatz, proved by Bridges, Mines, Richman and Schuster (see Bridges et al. (2004)), shows that the existence of a stable polynomial \( s \in I \) is equivalent to \( V(I) \cap \mathbb{C}^n = \emptyset \). Several proofs of this result have been investigated in the literature, mainly for the case where \( I \) is a zero-dimensional ideal (see Raman and Liu (1986); Lin (1988); Biasacco et al. (1986); Güiver and Bose (1995) and Xu et al. (1994) for instance). Nevertheless none of them is effective in the sense that it provides an algorithm for computing \( s \) using calculations that can be performed in an exact way by a computer. Indeed, starting from a set of polynomials with rational coefficients \( (I \subseteq \mathbb{Q}[z_1, \ldots, z_n]) \), these algorithms are built on spectral factorization, i.e., factorization of polynomials in \( \mathbb{Q}[z] \) into stable and instable factors. For irreducible polynomials in \( \mathbb{Q}[z] \), this factorization requires the explicit computation of the complex roots of the polynomials, which can be done only approximately. This leads to approximate (stable) polynomials that do not belong to the polynomial ideal. As a consequence, these algorithms are able to solve the aforementioned problem only for few simple systems (see Sections 4 and 5 for details).

Our second contribution is to provide an effective algorithm for computing a stable polynomial \( s = \sum_{i=1}^n u_i p_i \in I \) for the class of systems for which \( f \subseteq \mathbb{Q}[z_1, \ldots, z_n] \) is a zero-dimensional ideal. Our symbolic-numerical method roughly follows the lines of that proposed in Xu et al. (1994) but once again we take advantage of the univariate representation of zero-dimensional ideals (Rouillier (1999)) to control the numeric precision required to achieve our goal.

The paper is organized as follows. In Section 2, we recall some classical computer algebra results on the complex zeros of polynomials and polynomial systems. We also introduce the univariate representation of zero-dimensional ideals which will be our main tool in what follows. In Section 3, we provide an effective stabilizability test, i.e., an algorithm for testing whether a zero-dimensional ideal intersects the closed unit polydisc. In Section 4, we provide an effective polydisc Nullstellensatz namely a symbolic-numerical method for computing, if it exists, a stable polynomial in a zero-dimensional polynomial ideal. Finally, in Section 5, we illustrate our methods on one example and show some running times of prototype implementations.

### 2. PRELIMINARIES ON ALGEBRAIC SYSTEMS

In this section, we introduce some notations and we recall some classical material about the computation of certified numerical approximations of the complex zeros of polynomials and polynomial systems.

The bit-size of an integer is the number of bits in its representation and for a rational number (resp., a polynomial with rational coefficients) the term bit-size refers to the maximum bit-size of its numerator and denominator (resp., of its coefficients). For a complex number \( z \in \mathbb{C}^n \), we denote by \( \Re(z) \in \mathbb{R} \) (resp., \( \Im(z) \in \mathbb{R} \)) its real (resp., imaginary) part. If \( z_1, z_2 \in \mathbb{C}^n \), we write \( z_1 < z_2 \) if both \( \Re(z_1) < \Re(z_2) \) and \( \Im(z_1) < \Im(z_2) \). For \( z_1, z_2 \in \mathbb{C}^n \) such that \( z_1 < z_2 \), we shall consider the axes-parallel open box or box for short \( B = B(z_1, z_2) = \{ z \in \mathbb{C}^n \mid z_1 < z < z_2 \} \) and its width is defined by \( |B| = \max(|\Re(z_2) - \Re(z_1)|, |\Im(z_2) - \Im(z_1)|) \). We also introduce the non-negative real number \( |B| = \max(|\Re(z_1)|, |\Im(z_1)|, |\Re(z_2)|, |\Im(z_2)|) \). The box \( B \) is said to be of rational endpoints if \( z_1, z_2 \) have rational real and imaginary parts, i.e., \( \Re(z_1), \Im(z_1), \Re(z_2), \Im(z_2) \in \mathbb{Q} \).

Finally, the box \( B \) is called isolating for a given polynomial \( f \in \mathbb{Q}[z] \) if it contains exactly one complex root of \( f \).

The following result concerns the isolation of the complex zeros of a univariate polynomial. We refer, for instance, to Sagraloff and Yap (2009) for more details.

**Lemma 1.** Let \( f \in \mathbb{Q}[z] \) be a squarefree polynomial of degree \( d \). Then, for all \( \epsilon > 0 \), one can compute disjoint axes-parallel open boxes \( B_1, \ldots, B_d \) with rational endpoints such that each \( B_i \) contains exactly one complex root of \( f \) and satisfies \( \text{width}(B_i) \leq \epsilon \).

In the algorithms given in Sections 3 and 4 below, we shall use a routine called Isolate which takes as input a univariate polynomial \( f \), a box \( B \), and a precision \( \epsilon > 0 \) and computes isolating boxes \( B_1, \ldots, B_d \) with rational endpoints for the complex roots of \( f \) that lie inside the given box \( B \) and such that \( \text{max}_{i=1,\ldots,d} \text{width}(B_i) \leq \epsilon \). If \( B \) (resp., \( \epsilon \)) is not specified in the input, we consider all complex roots in \( \mathbb{C} \) (resp., the boxes are computed up to a sufficient precision for isolation).

Let us now recall a standard property about width expansion through interval arithmetic in polynomial evaluation. Here we consider exact interval arithmetic, that is, the arithmetic operations on the interval endpoints are considered exact (see Alefeld and Herzberger (2012)). If \( f \in \mathbb{Q}[x_1, x_2] \) is a bivariate polynomial of two real variables \( x_1 \) and \( x_2 \) and \( B \) a box, we denote by \( \overline{f}(B) \) the interval that results from the evaluation of the polynomial \( f \) at the box \( B \) using interval arithmetic.

**Lemma 2.** (Cheng et al. (2010), Lemma 8). Let \( B \) be a box with rational endpoints satisfying \( |B| \leq 2^d \) and let \( f \in \mathbb{Q}[x_1, x_2] \) be a bivariate polynomial of two real variables \( x_1 \) and \( x_2 \) of degree \( d \) with coefficients of bit-size \( \tau \). Then, \( f \) can be evaluated at the box \( B \) by interval arithmetic into an interval \( \overline{f}(B) \) of width at most \( 2^{\tau + d^2 + 1} \text{width}(B) \).

In particular, a direct consequence of Lemma 2 is that if \( \text{width}(B) \leq \epsilon 2^{-d^2 + 1} \log_2(d) \), then we have \( \text{width}(\overline{f}(B)) \leq \epsilon \).

We now consider a set of polynomials \( p_1, \ldots, p_n \) in \( \mathbb{Q}[z_1, \ldots, z_n] \). We denote by \( I = \langle p_1, \ldots, p_n \rangle \) the ideal generated by the \( p_i \)'s and by

\[ V(I) = \{ z \in \mathbb{C}^n \mid p_1(z) = \cdots = p_n(z) = 0 \} \subseteq \mathbb{C}^n, \]

the complex variety of their common zeros. In the sequel, we shall always assume that the ideal \( I \) under consideration is a zero-dimensional ideal, that is, that the \( p_i \)'s have only a finite number of common complex zeros, i.e., \( V(I) \)
consists of a finite number of complex points. Methods for computing certified numerical approximations for the elements of \( V(I) \) usually proceed in two steps. First, a formal representation (as for instance, a Gröbner basis, a triangular decomposition or a univariate representation) of the set \( V(I) \) is computed. Then, this formal representation is used to compute, more or less easily, numerical approximations of the elements of \( V(I) \). The convenient representation of the variety of zero-dimensional ideals that we shall use in the sequel is the so-called univariate representation introduced by Rouillier (1999).

**Definition 3.** With the previous notation and assumptions, a univariate representation of \( V(I) \) is the datum of a linear form \( t = a_1 z_1 + \cdots + a_n z_n \), with \( a_1, \ldots, a_n \in \mathbb{Q} \) as well as \( n+1 \) univariate polynomials \( f, g_1, \ldots, g_n \in \mathbb{Q}[t] \) such that the following two applications

\[
V(I) \longrightarrow V(f) = \{ z \in \mathbb{C} \mid f(z) = 0 \}
\]

\[
z = (z_1, \ldots, z_n) \mapsto a_1 z_1 + \cdots + a_n z_n,
\]

and

\[
V(f) \longrightarrow V(I)
\]

\[
z \mapsto (g_1(z), \ldots, g_n(z)),
\]

provide a one-to-one correspondence between the elements of \( V(I) \) and the zeros of \( f \).

The univariate representation then defines a bijection between the zeros of \( I \) and those of \( f \) that preserves the multiplicities and the real zeros. One of its main advantages is that it permits to study the variety \( V(I) \), i.e., the set of common zeros of the polynomials \( p_i \)'s of \( n \) variables through the roots of the univariate polynomial \( f \). In particular, if we are interested in computing certified numerical approximations of the complex elements of \( V(I) \), a first step consists, in isolating the complex roots of the polynomial \( f \) (using for instance the algorithm in Sagraloff and Yap (2009)). Then, numerical approximations of the coordinates \( z_1, \ldots, z_n \) of \( z \in V(I) \) can be obtained by evaluating \( g_1, \ldots, g_n \) at the obtained numerical boxes. Lemmas 1 and 2 above show that we can thus obtain a given precision for the elements of \( V(I) \).

The computation of a univariate representation of \( V(I) \) can be done by pre-computing a Gröbner basis \( G \) of the ideal \( I \) Cox et al. (1992), and then performing linear algebra calculations in the quotient vector space \( \mathbb{Q}[z_1, \ldots, z_n]/I \) which admits a basis composed of the monomials that are irreducible modulo the Gröbner basis \( G \). For more details, see Rouillier (1999). For the specific case of bivariate algebraic systems, it should be stressed that very practically efficient algorithms exist for computing such a representation; see Bouzidi (2014). To achieve efficiency, these algorithms replace the "costly" computation of a Gröbner basis of \( I \) by resultants and subresultants computations, see Basu et al. (2006).

In the algorithms given in Sections 3 and 4 below, we shall use a routine called \texttt{UnivR} which takes as input the polynomials \( p_1, \ldots, p_r \) and computes a univariate representation of the variety \( V(I) \) of the zero-dimensional ideal \( I = (p_1, \ldots, p_r) \).

3. AN EFFECTIVE STABILIZABILITY TEST

Using the fractional representation approach to multidimensional systems, in Section 1, we have seen that a plant is stabilizable if and only if \( V(I) \cap \mathbb{C}^n = \emptyset \) for a certain polynomial ideal \( I = (p_1, \ldots, p_r) \) that can be explicitly described in terms of the transfer matrix of the plant.

Given polynomials \( p_1, \ldots, p_r \in \mathbb{Q}[z_1, \ldots, z_n] \), the purpose of this section is to provide an effective algorithm to decide whether or not \( V(I) \cap \mathbb{C}^n = \emptyset \) for \( I = (p_1, \ldots, p_r) \) is a zero-dimensional ideal. To achieve this, we shall use a symbolic-numeric approach. We start by computing a univariate representation of \( V(I) \). As explained in Section 2, such a representation allows to describe formally the elements \( z = (z_1, \ldots, z_n) \) of \( V(I) \) as

\[
\{ f(t) = 0, \quad z_1 = g_{z_1}(t), \quad \ldots, \quad z_n = g_{z_n}(t) \} \quad (1)
\]

where \( f, g_1, \ldots, g_n \in \mathbb{Q}[t] \). In what follows, the degree of \( f \) is denoted by \( d \), and those of \( g_1, \ldots, g_n \) are then smaller than \( d \) (see Rouillier (1999)).

Using a univariate representation, one can compute a set of hypercubes in \( \mathbb{R}^{2n} \) isolating the elements of \( V(I) \). Each coordinate is represented by a box in \( \mathbb{R}^2 \) obtained from the intervals containing its real and imaginary parts. Moreover, from Lemmas 1 and 2, these hypercubes can be refined up to an arbitrary precision. We shall now consider the intersection between those hypercubes and the closed unit polydisc of \( \mathbb{C}^n \) defined by:

\[
\mathbb{U}^n = \{ z = (z_1, \ldots, z_n) \in \mathbb{C}^n \mid |z_1| \leq 1, \ldots, |z_n| \leq 1 \}.
\]

Below, for any \( g_i \in \mathbb{Q}[t] \), we shall denote by \( \mathfrak{C}(g_i) \) the bivariate polynomial \( \mathfrak{R}(g_i)^2 + 3g_i^2 - 1 \in \mathbb{Q}[x_1, x_2] \), where \( \mathfrak{R}(g_i) \) (resp., \( 3g_i \) ) is the real (resp., complex) part of the polynomial resulting from \( g_i(x_1 + i x_2) \).

From the definition of \( \mathbb{U}^n \), one can see that the situation is easier when \( V(I) \) does not contain elements \( z \in \mathbb{C}^n \) with \( |z_1| = 1 \) for some \( i \in \{1, \ldots, r\} \). Indeed, we have:

**Theorem 4.** With the previous notations, let us consider \( z = (z_1, \ldots, z_n) \in V(I) \) such that, for all \( i \in \{1, \ldots, n\} \), \( |z_i| \neq 1 \). Let \( B \) be an isolating box for the root of \( f \) corresponding to \( z \) in the univariate representation of \( V(I) \). Then, there exists \( \epsilon > 0 \) such that if \( w(B) \leq \epsilon \), then, for all \( k \in \{1, \ldots, n\} \), the interval \( \mathfrak{C}(g_i)(B) \) does not contain zero.

**Proof.** Let \( d \) (resp., \( \tau \) ) denote an upper bound on the degree (resp., bit-size) of the polynomials \( g_i, k = 1, \ldots, n \). For \( k \in \{1, \ldots, n\} \), the real (resp., imaginary) part of the bivariate polynomial \( g_i(x_1 + i x_2) \) is a bivariate polynomial in \( x_1 \) and \( x_2 \) of degree (resp., bit-size) bounded by \( d \) (resp., \( d + \tau \) ). Consequently, the bivariate polynomial \( \mathfrak{C}(g_i) \in \mathbb{Q}[x_1, x_2] \) has degree and bit-size respectively bounded by \( 2d \) and \( (d + \tau) \) respectively. Now, for \( z = (z_1, \ldots, z_n) \in V(I) \), let \( m = \min_{k=1, \ldots, n} |z_k| - 1 > 0 \) and let \( B \) be an isolating box for the root of \( f \) corresponding to \( z \) in the univariate representation of \( V(I) \) (1), and such that \( |B| \leq 2^\tau \). From Theorem 2, if we refine \( B \) so that \( w(B) \leq \epsilon \), where \( \epsilon = m 2^{-(d+\tau)} d^{-2} d \sigma^{-3} \log(2d) \), then, we have that for all \( k \in \{1, \ldots, n\} \), the interval \( \mathfrak{C}(g_i)(B) \) satisfies \( w(\mathfrak{C}(g_i)(B)) \leq m \) so that, by definition of \( m \), it does not contain zero.

Therefore, if \( V(I) \) does not contain elements \( z \in \mathbb{C}^n \) with one coordinate \( z_1 \) in the unit circle, one can easily test...
the stabilizability condition \( V(I) \cap \overline{U}^n = \emptyset \). Indeed, with the
previous notations, we isolate the roots of \( f \) inside boxes \( B_1, \ldots, B_d \). Then, for \( i \in \{1, \ldots, d\} \),
we refine \( B_i \) until, for all \( k \in \{1, \ldots, n\} \), the interval \([\bar{C}(g_k), (B_i)]\) does
not contain zero. If one of the intervals \([\bar{C}(g_k), (B_i)]\) is
included in \( \mathbb{R}_+ \), we proceed to the next box \( B_i \), otherwise
we have found an element in \( V(I) \cap \overline{U}^n \) so that the system is
certainly not stabilizable. After having investigated all the
boxes \( B_i \), we can then conclude about the stabilizability of
the system.

We shall now consider the case where \( V(I) \) contains (at
least) one element having some coordinates on the unit
circle. In this case, we cannot proceed numerically as
before since if \( |z_k| = 1 \), then, using the above notations,
we cannot fulfill the condition that the interval \([\bar{C}(g_k), (B_i)]\)
do not contain zero. To guarantee the termination of the
algorithm, we shall then have to compute, for each variable
\( z_k \), the number of elements \( z = (z_1, \ldots, z_n) \in V(I)
satisfying \( |z_k| = 1 \).

Lemma 5. Let \( I \subset \mathbb{Q}[z_1, \ldots, z_n] \) be a zero-dimensional
ideal and \( V(I) \) the associated algebraic variety. Then, for
all \( k \in \{1, \ldots, n\} \), one can compute the non-negative integer
\( l_k = \sharp \{z = (z_1, \ldots, z_n) \in V(I) \mid |z_k| = 1\} \).

Proof. Let \( \{f(t), z_1 - g_{1}(t), \ldots, z_n - g_{n}(t)\} \) be a univariate
representation of \( V(I) \) and \( k \in \{1, \ldots, n\} \). Computing
the resultant of the polynomials \( f \) and \( z_k - g_{k} \) with
respect to the variable \( t \) we get a univariate polynomial that can be
written \( r_k = \prod_{t \in V(I)} (z_k - \alpha_{k})^{\mu_{\alpha_{k}}} \), where the
multiplicity \( \mu_{\alpha_k} \) corresponds to \( \sharp \{z \in V(I) \mid z_k = \alpha_k\} \).
Then, using the classical Bistritz test (see Bistritz (2002)),
one can compute the number of complex roots counted
with multiplicity of \( r_k \) that lie on the unit circle and obtain
the non-negative integer \( l_k \).

Remark 1. An alternative to the Bistritz test, which we
use in practice, consists in applying to the polynomial \( r_k \),
the Möbius transform \( z_k \to \frac{z_k - 1}{z_k + 1} \) which maps the complex
unit circle \( \mathbb{U} \) to the real line \( \mathbb{R} \cup \{\infty\} \). The number of
critical roots of \( r_k \) on the unit circle is then given as the
number of real roots of the gcd of two polynomials \( R \) and
\( \mathcal{S} \), where \( R \) (resp., \( \mathcal{S} \)) is the real (resp., complex) part of
the numerator of the rational fraction \( \frac{r_k(z_k - 1)}{z_k + 1} \).

Using Lemma 5, we can test the stabilizability condition
\( V(I) \cap \overline{U}^n = \emptyset \) as follows. We start with the variable \( z_1 \).
We refine the isolating boxes \( B_{1, \ldots, B_d} \) for the roots of \( f \) until
exactly \( l_1 \) intervals \( \bigcap C(g_{k_1})(B_i) \) contain zero. We throw
away the boxes \( B_i \)'s such that the interval \([\overline{C}(g_k), (B_i)]\) is
included in \( \mathbb{R}_+ \) and we proceed similarly with the next
variable \( z_2 \). If at some point we have thrown away all
the boxes \( B_i \)'s, then the system is stabilizable. Otherwise
the boxes which remain at the end of the process lead to
elments of \( V(I) \cap \overline{U}^n \) so that the system is not stabilizable.

We summarize our symbolic-numeric method for testing
stabilizability in the following IsStabilizable algorithm.

4. AN EFFECTIVE STABILIZATION ALGORITHM

When a multidimensional system is stabilizable, one is
then interested in computing a stabilizing controller.
Within the fractional representation approach, this prob-
lem reduces to the following task (see Section 1 or Lin
(1988)): given a polynomial ideal \( I = (p_1, \ldots, p_r) \) satisfying
\( V(I) \cap \overline{U}^n = \emptyset \), compute a polynomial \( s \in \mathbb{Q}[z_1, \ldots, z_n]\)
such that \( s \) belongs to the ideal \( I \) and \( s \) is a stable
polynomial, i.e., \( s \) is devoid from zeros in \( \overline{U}^n \).

For an ideal \( I \subset \mathbb{Q}[z_1, \ldots, z_n] \), the polydisc
Nullstellensatz (see Bridges et al. (2004)) asserts that the
existence of a stable polynomial \( s \in I \) is equivalent to \( V(I) \cap \overline{U}^n = \emptyset \).

Theorem 6. (Polydisc Nullstellensatz). Let us consider a
polynomial ideal \( I = \langle p_1, \ldots, p_r \rangle \subset \mathbb{Q}[z_1, \ldots, z_n] \) such
that \( V(I) \cap \overline{U}^n = \emptyset \). Then, there exist \( r + 1 \) polynomials
\( s, u_1, \ldots, u_r \in \mathbb{Q}[z_1, \ldots, z_n] \) such that:

\[
 s = \sum_{i=1}^{r} u_i \cdot p_i \quad \text{and} \quad V(s) \cap \overline{U}^n = \emptyset.
\]

Algorithm 1 IsStabilizable

Input: A set of \( r \) polynomials \( p_1, \ldots, p_r \subset \mathbb{Q}[z_1, \ldots, z_n] \).
Output: True if \( V(p_1, \ldots, p_r) \cap \overline{U}^n = \emptyset \), else False.

Begin
\( \bigcirc \{f,g_2, \ldots, g_n\} := \text{Univ}_R\langle p_1, \ldots, p_r \rangle \); \n\( \{B_1, B_2 \} := \text{Isolate}(f) \); \n\( L_B := \{B_1, B_2 \} \) and \( \epsilon := \min_{1, \ldots, d}(w(B_i)) \);

For \( k \) from 1 to \( n \) do
\( l_k := \sharp \{z \in V(I) \mid |z_k| = 1\} \) (see Lemma 5);
\While \( \sharp \{i \mid 0 \in \overline{C}(g_k)(B_i)\} > l_k \) do
\( \epsilon := \epsilon/2 \);
\For \( i = 1, \ldots, d \) set : \( B_i := \text{Isolate}(f, B_i, \epsilon) \);
\EndWhile
\( L_B := L_B \setminus \{B_1, B_2, \ldots, B_r \} \)
\If \( L_B = \{\} \) then Return True End If;
\EndFor
Return False.

End

Several proofs of Theorem 6 have been investigated in the
literature. Nevertheless none of them is effective in the
sense that it provides an algorithm for computing \( s \) and
the cofactors \( u_i \)'s using calculations that can be performed
in an exact way by a computer. In Xu et al. (1994), the
authors study 2D systems (i.e., \( n = 2 \)) for which the ideal \( I \)
under consideration is zero-dimensional. The idea of their
method for computing a stable polynomial \( s \in I \) is to
compute univariate elimination polynomials \( r_{z_1} \in \mathbb{Q}[z_1] \)
and \( r_{z_2} \in \mathbb{Q}[z_2] \) with respect to each variable \( z_1 \) and
\( z_2 \) and to factorize them into a stable and an unstable
factor, i.e., for \( i = 1, 2 \), \( r_{z_1} = r_{z_1}^{(s)} r_{z_2}^{(u)} \), where the roots of
\( r_{z_1}^{(s)} \) (resp., \( r_{z_2}^{(u)} \)) are outside (resp., inside) the closed
unit disc \( \overline{U} \) and, then, to compute the stable polynomial
\( s = r_{z_1}^{(s)} r_{z_2}^{(s)} \). However, this approach presents a major
drawback with respect to the effectiveness aspect. Indeed,
when the elimination polynomial \( r_{z_1} \) (resp., \( r_{z_2} \)) is
an irreducible polynomial in \( \mathbb{Q}[z_1] \) (resp. \( \mathbb{Q}[z_2] \)), its stable
factor \( r_{z_1}^{(s)} \) (resp., \( r_{z_2}^{(s)} \)) could not be computed exactly
since it will have coefficients in \( \mathbb{C} \), and thus, only an
approximation of this polynomial can be obtained. As
a consequence, the polynomial \( s = r_{z_1}^{(s)} r_{z_2}^{(s)} \) will not belong
to the ideal \( I \).

In the sequel, we present a symbolic-numeric algorithm for
computing \( s \) and the \( u_i \)'s that follows roughly the approach
of Xu et al. (1994) while we provide a way for tackling the effectiveness issue. Our main ingredient is the univariate representation of zero-dimensional ideals which allows us to compute and refine approximate factorizations over \( \mathbb{Q} \) of the elimination polynomials \( r_s \)’s.

Let \( I = \langle p_1, \ldots, p_r \rangle \subset \mathbb{Q}[z_1, \ldots, z_n] \) be a zero-dimensional ideal such that \( V(I) \cap \mathbb{U}^n = \emptyset \). For simplicity reasons, in what follows, we further assume that the ideal \( I \) is radical, i.e., \( \sqrt{I} = \{ p \in \mathbb{Q}[z_1, \ldots, z_n] \mid 3m \in \mathbb{N}^*, \ p^m \in I \} = I \). The elements \( z = (z_1, \ldots, z_n) \) of \( V(I) \) are given by a univariate representation \[
\{ f(t) = 0, \quad z_1 = g_{1}(t), \ldots, \quad z_n = g_{n}(t), \quad \}
\] where \( t = a_1 z_1 + \cdots + a_n z_n, \ a_k \in \mathbb{R} \) for \( k = 1, \ldots, n \), \( f, g_1, \ldots, g_n \in \mathbb{Q}[t] \), and \( \deg(f) = d \). Since \( I \) is a radical ideal, the polynomial \( f \) is a squarefree polynomial and \( f(t) = \prod_{i=1}^d (t - \gamma_i) \) for distincts \( \gamma_1, \ldots, \gamma_d \in \mathbb{C} \). Moreover, from Definition 3.1, if we introduce the polynomial ideal \( I_r = \langle f(t), z_1 - g_{1}(t), \ldots, z_n - g_{n}(t) \rangle \subset \mathbb{Q}[t, z_1, \ldots, z_n] \), then we have \( I_r = \mathbb{I} \cap \{ t - \gamma_i \} \) for \( i \in \{ 1, \ldots, d \} \) and \( \gamma_i \in \mathbb{C} \). In particular, if \( p(t, z_1, \ldots, z_n) \in I_r \), then \( p(t, z_1, \ldots, z_n) \in \mathbb{I} \), and \( \mathbb{I} \) is stable.

Let us first explain how we can compute approximations \( \tilde{r}_s^{(k)} \) of the stable polynomials \( r_s^{(k)} \) appearing in the method of Xu et al. (1994) described above. Using Lemma 1, we can compute a set of boxes \( B_1, \ldots, B_d \) with rational endpoints, isolating the distinct complex roots \( \gamma_1, \ldots, \gamma_d \) of \( f \). Then, according to the stability-lemma condition \( V(I) \cap \mathbb{U}^n = \emptyset \), for all \( i \in \{ 1, \ldots, d \} \), the box \( B_i \) can be refined so that there exists \( k \in \{ 1, \ldots, n \} \) satisfying \( \mathbb{C} \cap r(z_k) \cap (B_i) \in \mathbb{R} \). We then set \( \gamma_i \in \mathbb{Q} \) to the midpoint of the refined box \( B_i \) and add the factor \( z_k - g_{k}(\gamma_i) \) to the polynomial \( \tilde{r}_k^{(s)} \). We finally obtain a set of stable univariate polynomials \( \tilde{r}_k^{(s)} \in \mathbb{Q}[z_k], k = 1, \ldots, n \) such that \( \sum_{k=1}^n \deg(\tilde{r}_k^{(s)}) = d \).

Let us now introduce the stable \( \tilde{s} \in \{ z_1, \ldots, z_n \} \) with rational coefficients and which vanishes on \( V(I_r) \), where the polynomial ideal \( I_r \) is defined by \( I_r = \langle f(t), z_1 - g_{1}(t), \ldots, z_n - g_{n}(t) \rangle \) with \( f(t) = \prod_{i=1}^d (t - \gamma_i) \in \mathbb{Q}[t] \). Hence, according to the classical Nullstellensatz theorem (Cox et al. (1992)), \( \tilde{s} \) belongs to the ideal \( I_r \) so that there exist polynomials \( \tilde{h}_0, \tilde{h}_1, \ldots, \tilde{h}_n \in \mathbb{Q}[t, z_1, \ldots, z_n] \) such that \( \tilde{s} = \tilde{h}_0 f + \sum_{k=1}^n \tilde{h}_k (z_k - g_{z_k}) \). Moreover \( \tilde{h}_0 \) can be explicitly computed as the quotient of the Euclidean division of \( \tilde{s}(g_{1}(t), \ldots, g_{n}(t)) \) by \( f(t) \) in \( \mathbb{Q}[t] \).

We shall now show that if we refine enough the boxes \( B_i \)’s isolating the roots \( \gamma_i \) of \( f \), then the stable polynomial \( s \in I \) that we are seeking for can be obtained from the polynomials \( \tilde{s} \) and \( \tilde{h}_0 \) constructed as explained above. For \( \epsilon > 0 \), we denote \( \tilde{s}_\epsilon, \tilde{h}_\epsilon, f_\epsilon(t) = \prod_{i=1}^d (t - \tilde{\gamma}_i, \epsilon) \), and \( \tilde{h}_\epsilon \) the objects constructed by the previous process where the roots of \( f \) are isolated up to precision \( \epsilon \) (i.e., \( w(B_i) < \epsilon \)), for all \( i \in \{ 1, \ldots, d \} \). Using the previous notations, the main result of this section can be stated as follows:

**Theorem 7.** The polynomial \( s = \tilde{s}_\epsilon - \tilde{h}_\epsilon f_\epsilon \) belongs to the ideal \( I_r \). Moreover, there exists \( \epsilon > 0 \) such that the polynomial \( s = \sum_{i=1}^n a_i z_i, z_1, \ldots, z_n \) is a stable polynomial.

---

1. Small enough so that the previous process can be applied.
have $|\lambda_k| - |g_{z_k}(\tilde{\gamma}_{i,\epsilon})| \geq m - \epsilon$, which yields:
\[ \forall \lambda \in \mathbb{U}^n, \ |s(\lambda)| \geq (m - \epsilon)^d. \]
Finally, for sufficiently small $\epsilon$, we have $(m - \epsilon)^d > \epsilon \rho \delta$ so that:
\[ \forall \lambda \in \mathbb{U}^n, \ |s(\lambda)| \geq |\hat{s}(\lambda)| - |h_{0,\epsilon}(\lambda)(\hat{f}(\lambda) - f(\lambda))| \geq (m - \epsilon)^d - \epsilon \rho \delta > 0, \]
which ends the proof.

The following StablePolynomial algorithm summarizes our method for computing a stable polynomial in a zero-dimensional ideal $I$ satisfying $V(I) \cap \mathbb{U}^n = \emptyset$. The routine IsStable is used to test if a polynomial $p \in \mathbb{Q}[z_1, \ldots, z_n]$ is stable, i.e., if $V(p) \cap \mathbb{U}^n = \emptyset$ (see Bouzidi et al. (2015); Bouzidi and Rouillier (2016)).

**Algorithm 2 StablePolynomial**

**Input:** $I := \langle p_1, p_2 \rangle$ be such that $V(I) \cap \mathbb{U}^n = \emptyset$.

**Output:** $s \in I$ such that $V(s) \cap \mathbb{U}^n = \emptyset$.

**Begin**
\[ \{ f, g_1, \ldots, g_n \} := \text{UnivB}(\{ p_1, p_2 \}); \]
\[ \{ B_1, \ldots, B_d \} := \text{Isolate}(f); \]
\[ \epsilon := \min_{i=1,\ldots,d} w(B_i); \]
\[ \text{Do} \]
\[ \text{For each } B \text{ in } \{ B_1, \ldots, B_d \} \]
\[ \text{While (outside=False) do} \]
\[ \text{For } i \text{ from } 1 \text{ to } n \text{ do} \]
\[ \text{If } CC(g_i)(B) \subset \mathbb{R}_+ \text{ then} \]
\[ \gamma := \text{midpoint}(B); \]
\[ r_i := r_i(z_i - g_i(\gamma)); \]
\[ \text{outside} := \text{True} \text{ and Break For;} \]
\[ \text{End If} \]
\[ \text{End For} \]
\[ \epsilon := \epsilon/2; \]
\[ B := \text{Isolate}(f, B, \epsilon); \]
\[ \text{End While} \]
\[ \hat{f} := \hat{f}(t - \gamma); \]
\[ \text{outside} := \text{False}; \]
\[ \text{End ForEach} \]
\[ \hat{s} := \prod_{i=1}^n r_i; \]
\[ \hat{s}_i := \hat{s} \text{ evaluated at } z_i = g_i(t); \]
\[ h_0 := \text{quotient}(\hat{s}_i, \hat{f}) \text{ in } \mathbb{Q}[t]; \]
\[ s := \hat{s} - h_0(\hat{f} - f) \text{ evaluated at } t = \sum_{k=1}^n a_k z_k; \]
\[ \text{While (IsStable(s)=False) do} \]
\[ \text{Return } s. \]

5. EXAMPLES AND EXPERIMENTS

Let us illustrate the algorithm of Section 4 on the following simple example:

\[ I = \langle p_1, p_2 \rangle, \quad p_1 = z_1^2 - 2z_1 - 2, \quad p_2 = z_1 + z_2 - 2. \]

The associated variety $V(I)$ contains two elements, namely, $(1 - \sqrt{3}, 1 + \sqrt{3})$ and $(1 + \sqrt{3}, 1 - \sqrt{3})$, so that the stabilizability condition $V(I) \cap \mathbb{U}^n = \emptyset$ is clearly fulfilled. Yet, $p_1$ and $p_2$ are both unstable polynomials. For $i \in \{1, 2\}$, the univariate elimination polynomials (i.e., the resultants of $p_1$ and $p_2$) $r_{z_i} \in \mathbb{Q}[z_i]$ is given by $r_{z_i} = z_i^2 - 2z_i - 2$.

Finally, after substituting $t = z_1$ in $\hat{f} - f$, we get:
\[ s(z_1, z_2) = z_1 z_2 - 3 z_1 - 3 z_2 + 8. \]

We can then check that this polynomial is stable so that we are done (see Bouzidi et al. (2015)). As a byproduct, we also obtain the corresponding cofactors, that is, $s = -p_1 + (z_1 - 3) p_2 \in I$.

Figure 1 shows the stable polynomial obtained by an exact factorization of $r_{z_1}$ and $r_{z_2}$ in dots, the approximate factorization $\hat{s}$ used in our algorithm in dash, and finally the stable polynomial $s$ obtained after adding the correcting term represented by the solid curve.
We have implemented two routines \texttt{StablePolynomial} and \texttt{IsStabilizable}, which correspond respectively to the algorithms given in Sections 3 and 4, in the computer algebra system Maple. These routines use the procedure \texttt{resultant} for computing the resultant of two polynomials (required in the computation of $l_k$ in Algorithm 3), the procedure \texttt{RationalUnivariateRepresentation} of the Maple package\texttt{Groebner} for computing the \texttt{Rational Univariate Representation} of a zero-dimensional ideals, and the procedure \texttt{fsolve} for computing the complex roots of a univariate polynomial.

In Table 1 below, we report the running times (in seconds) of \texttt{StablePolynomial} and \texttt{IsStabilizable} applied to systems of randomly chosen polynomials in two or three variables with integer coefficients chosen uniformly at random between $-100$ and $100$. In order to get zero-dimensional systems, we choose as many polynomials as number of variables. Moreover, we use the change of variables $z_i = Z_i/10$, $i = 1, 2$ or $i = 1, 2, 3$ to increase the probability of the roots to be outside the unit polydisc. The experiments have been conducted on 2.10 GHz Core(TM) Intel i7-4600U with 4MB of L3 cache with Maple 2015 under windows platform.

\textbf{Remark 2.} From Table 1, one can notice that, in general, the running times of \texttt{IsStabilizable} are higher than those of \texttt{StablePolynomial}. This is, most likely, due to the additional cost induced by the computation of $l_k$ in Algorithm 3, which requires the computation of elimination polynomials for each variable (resultants).

<table>
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</table>

Table 1. CPU times in seconds of \texttt{IsStabilizable} and \texttt{StablePolynomial} runned on sets of random polynomials in 2 or 3 variables with integer coefficients.

\begin{thebibliography}{99}


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