Computing with Semi-Algebraic Sets Represented by Triangular Decomposition

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ABSTRACT
This article is a continuation of our earlier work [3], which introduced triangular decompositions of semi-algebraic systems and algorithms for computing them. Our new contributions include theoretical results based on which we obtain practical improvements for these decomposition algorithms.

We exhibit new results on the theory of border polynomials of parametric semi-algebraic systems: in particular a geometric characterization of its “true boundary” (Definition 2). In order to optimize these algorithms, we also propose a technique, that we call relaxation, which can simplify the decomposition process and reduce the number of redundant components in the output. Moreover, we present procedures for basic set-theoretical operations on semi-algebraic sets represented by triangular decomposition. Experimentation confirms the effectiveness of our techniques.

1. INTRODUCTION
Triangular decompositions of semi-algebraic systems were introduced in [3]. The key notions and notations of this paper are reviewed in the next section.

That paper presents also an algorithm for generating those decompositions. This algorithm can either be eager, computing the entire decomposition, or lazy, only computing the decomposition corresponding to the highest (complex) dimensional components, and deferring lower-dimensional components. While a complete decomposition is known to have a worst-case complexity which is doubly-exponential in the number of variables [8], under plausible assumptions the lazy variant has a singly-exponential complexity. Nevertheless, it is still desirable to improve the practical efficiency of both types of decomposition.

The notion of a border polynomial [15] is at the core of our work. A strongly related notion, discriminant variety, was introduced in [9] and the link between them was investigated in [14]. Other similar but more restrictive notions like “generalised discriminant” and “generalised resultant” were introduced in [10]. For a squarefree regular chain T, regarded as a real parametric system in its free variables u, the border polynomial $BP(T)$ encodes the locus of the u-values at which T has lower rank or at which T is no longer a squarefree regular chain. (See §2 for the notions related to triangular decomposition and regular chains.) Consequently, for each connected component C of the complement of the real hypersurface defined by $BP(T)$ the number of real solutions of the regular chain T is constant at any point of C. However, $BP(T)$ is not an invariant of the variety $W(T)$, which is a bottleneck in designing better algorithms based on the notion of a border polynomial. We overcome this difficulty in two ways.

Firstly, in §3, we prove that among all regular chains $T'$ satisfying $\text{sat}(T') = \text{sat}(T)$ there is one and only one (characterized in Theorem 1) for which $BP(T')$ is minimal w.r.t. inclusion. Secondly, in §4, we introduce the concept of an effective boundary of a squarefree semi-algebraic system, see Definition 2. This allows us to identify a subset of $BP(T)$ which is an invariant of $W(T)$, that is, unchanged when replacing T by $T'$ as long as $W(T) = W(T')$ holds. In many ways, our notion of effective boundary is similar to the “better projection” ideas in the classical [7, and many others] approach to cylindrical algebraic decomposition.

In §5, we introduce the technique of relaxation which we shall motivate by an example. Consider the semi-algebraic system $sys = \{ f = 0, x - b > 0 \}$, where $f = ax^3 + bx - a$ for the variable ordering $a < b < x$. The LazyRealTriangularize algorithm of [3] will compute the border polynomial set $B = \{ a, b_1, b_2 \}$ and the fingerprint polynomial set (FPS) $F = \{ a, b_1, b_2, b, p_1, p_2, p_3 \}$, where $b_1 = ab^3 + b^2 - a$, $b_2 = 27a^2 + 4b^3$, $p_1 = 2b^3 + 1$, $p_2 = b^3 - 4$ and $p_3 = b - 1$. Thus the LazyRealTriangularize(sys) will produce 1 regular semi-algebraic system $S_1 = \{ f = 0, x - b > 0 \}$, and 7 unevaluated recursive calls, where
We summarize below the notions and notations of [3], including triangular decompositions of semi-algebraic systems.

**Zero sets and topology.** In this paper, we use “\( \mathbb{Z} \)” to denote the zero set of a polynomial system, involving equations and inequations, in \( \mathbb{C}^n \) and “\( \mathbb{Z}\mathbb{R} \)” to denote the zero set of a semi-algebraic system in \( \mathbb{R}^n \). If a semi-algebraic set \( S \) is finite, we denote by \( \#(S) \) the number of distinct points in it. In \( \mathbb{R}^n \), we use the Euclidean topology; in \( \mathbb{C}^n \), we use the Zariski topology. Given a semi-algebraic set \( S \), we denote by \( \partial S \) the boundary of \( S \), by \( \overline{S} \) the closure of \( S \).

**Notations on polynomials.** Throughout this paper, all polynomials are in \( \mathbb{Q}[x] \), with ordered variables \( x = x_1 < \cdots < x_n \). We order monomials of \( \mathbb{Q}[x] \) by the lexicographical ordering induced by \( x_1 < \cdots < x_n \). Then, we require that the leading coefficient of every polynomial in a regular chain or in a border polynomial set (defined hereafter) is equal to 1. Let \( F \subseteq \mathbb{Q}[x] \). We denote by \( V(F) \) the set of common zeros of \( F \) in \( \mathbb{C}^n \). Let \( p \) be a polynomial in \( \mathbb{Q}[x] \). Then denote by \( \text{mvar}(p) \), \( \text{init}(p) \), and \( \text{mdeg}(p) \) respectively the greatest variable appearing in \( p \) (called the main variable of \( p \)), the leading coefficient of \( p \) w.r.t. \( \text{mvar}(p) \) (called the initial of \( p \)), and the degree of \( p \) w.r.t. \( \text{mvar}(p) \) (called the main degree of \( p \)). Let \( v \in \mathbb{R} \). Denote by \( \text{lc}(p,v), \text{deg}(p,v), \text{der}(p,v), \text{discrim}(p,v) \) respectively the leading coefficient, the degree, the derivative and the discriminant of \( p \) w.r.t. \( v \).

**Triangular set.** Let \( T \subseteq \mathbb{Q}[x] \) be a triangular set, that is, a set of non-constant polynomials with pairwise distinct main variables. Denote by \( \text{mvar}(T) \) the set of main variables of the polynomials in \( T \). A variable \( v \) in \( x \) is called algebraic w.r.t. \( T \) if \( v \in \text{mvar}(T) \), otherwise it is said free w.r.t. \( T \). If no confusion is possible, we shall always denote by \( u = u_1, \ldots, u_d \) and \( y = y_1, \ldots, y_m \) \((m + d = n)\) respectively the free and the main variables of \( T \). When \( T \) is regarded as a parametric system, the free variables in \( T \) are its parameters.

Let \( h_T \) be the product of the initials of the polynomials in \( T \). We denote by \( \text{sat}(T) \) the saturated ideal of \( T \): if \( T \) is the empty triangular set, then \( \text{sat}(T) \) is defined as the trivial ideal \( (0) \), otherwise it is the colon ideal \( (T); : h_T \). The quasi-component \( W(T) \) of \( T \) is defined as \( V(T) \setminus V(h_T) \). Denote by \( W(T) \) the Zariski closure of \( W(T) \), which is equal to \( V(\text{sat}(T)) \). Denote by \( W_T \) the set \( Z_\mathbb{C}(T) \setminus Z_\mathbb{C}(h_T) \).

**Iterated resultant.** Let \( p,q \in \mathbb{Q}[x] \backslash \mathbb{Q} \). Let \( v = \text{mvar}(q) \). Denote by \( \text{res}(p,v) \) the resultant of \( p,q \) w.r.t. \( v \). Let \( T \subseteq \mathbb{Q}[x] \) be a triangular set. We define \( \text{res}(p,T) \) inductively: if \( T \) is empty, then \( \text{res}(p,T) = p \); otherwise let \( v \) be the largest variable occurring in \( T \), then \( \text{res}(p,T) = \text{res}(\text{res}(p,T_v),v) \).\( T_v \) and \( T_{<v} \) denote respectively the polynomials of \( T \) with main variables equal to and less than \( v \).

**Regular chain.** A triangular set \( T \subseteq \mathbb{Q}[x] \) is called a regular chain if either \( T \) is empty; or (letting \( t \) be the polynomial in \( T \) with maximum main variable) \( T \setminus \{t\} \) is a regular chain, and the initial of \( t \) is regular w.r.t. \( \text{sat}(T \setminus \{t\}) \). Let \( H \subseteq \mathbb{Q}[x] \). The pair \( [T,H] \) is a regular system if each polynomial in \( H \) is regular modulo \( \text{sat}(T) \). A regular chain \( T \) or a regular system \( [T,H] \), is squarefree if for all \( t \in T \), \( \text{det}(t) \) is

2. **TRIANGULAR DECOMPOSITION**
regular w.r.t. sat(T). Given \( u \in \mathbb{R}^d \), we say that a squarefree regular system \([T, H]\) specializes well at \( u \) if \( h_2^*(u) \neq 0 \) and \([T(u), H(u)]\) is a squarefree regular system. A regular chain is called \( d \)-dimensional if it has \( d \) free variables.

**Semi-algebraic system.** Consider four finite polynomial sets
\[F = \{f_1, \ldots, f_s\}, \quad N = \{n_1, \ldots, n_k\}, \quad P = \{p_1, \ldots, p_r\}, \quad H = \{h_1, \ldots, h_t\}\]
of \( \mathbb{Q}[x] \). Let \( \mathbb{N}_\geq \) denote the set of non-negative integers \( \{n_1 \geq 0, \ldots, n_k \geq 0\} \), let \( P_2 \) denote the set of positive inequalities \( \{p_1 > 0, \ldots, p_r > 0\} \), let \( H_\phi \) denote the set of inequations \( \{h_1 \neq 0, \ldots, h_t \neq 0\} \). We denote by \( \mathcal{S} = [F, N_\geq, P_2, H_\phi] \) the semi-algebraic system (SAS) defined as the conjunction of the constraints \( f_1 = \cdots = f_s = 0, N_\geq, P_2, H_\phi \). When \( N_\geq, H_\phi \) are empty, \( \mathcal{S} \) is called a basic semi-algebraic system and denoted by \([F, P]\).

**Regular semi-algebraic system.** We call a basic SAS \([T, P]\) in \( \mathbb{Q}[u, y] \) a squarefree semi-algebraic system, SFSAS for short, if \([T, P]\) forms a squarefree regular system. Let \([T, P]\) be an SFSAS. Let \( \mathcal{Q} \) be a quantifier-free formula of \( \mathbb{Q}[u] \). We say that \( R := \{Q, T, P\} \) is a regular semi-algebraic system if

(i) \( Q \) defines a non-empty open semi-algebraic set \( S \) in \( \mathbb{R}^d \);
(ii) \([T, P]\) specializes well at every point of \( S \);
(iii) at each \( u \in S \), the specialized system \([T(u), P(u)]\) has at least one real zero.

**Border polynomial [15, 16, 3].** We review briefly the notion of border polynomial of a regular chain, a regular system, or an SFSAS. Let \( R \) be either a squarefree regular chain \( T \), or a squarefree regular system \([T, P]\), or an SFSAS \([T, P]\) in \( \mathbb{Q}[x] \). We denote by \( B_{\text{sep}}(T) \), \( B_{\text{ins}}(T) \), \( B_{\text{ineq}}([T, P]) \) the set of irreducible factors of \( \prod_{f \in T} \text{res}(\text{discrim}(t, \text{mvar}(t)), T), \prod_{f \in P} \text{res}(f, T) \), respectively. Denote by \( \text{BP}(R) \) the set \( B_{\text{sep}}(T) \cup B_{\text{ins}}(T) \cup B_{\text{ineq}}([T, P]) \). Then \( \text{BP}(R) \) (resp. the polynomial \( \prod_{f \in \text{BP}(R)} f \)) is called the border polynomial set (resp. border polynomial) of \( R \).

**Lemma 1 (Lemma 2 in [3]).** Let \( R = [T, P] \) be an SFSAS of \( \mathbb{Q}[x] \). Let \( u_1, u_2 \) be two parameter values in a same connected component of \( Z_R(\prod_{f \in \text{BP}(R)} f \neq 0) \) in \( \mathbb{R}^d \). Then
\[\#Z_R(R(u_1)) = \#Z_R(R(u_2)).\]

**Fingerprint polynomial set.** \( R = [B_\phi, T, P] \) is called a pre-regular semi-algebraic system, if for each \( p \in \text{BP}([T, P]) \), \( p \) is a factor of some polynomial in \( B \). Suppose \( R \) is a pre-regular semi-algebraic system. A polynomial set \( D \subset \mathbb{Q}[u] \) is called a fingerprint polynomial set (FPS) of \( R \) if:

(i) \( Z_R(D_{\phi}) \subseteq Z_R(B_\phi) \) holds,
(ii) for all \( \alpha, \beta \in Z_R(D_{\phi}) \) with \( \alpha \neq \beta \), if the signs of \( p(\alpha) \) and \( p(\beta) \) are the same for all \( p \in D \), then \( R(\alpha) \) has real solutions if and only if \( R(\beta) \) does.

**Open CAD operator [12, 2, 3].** Let \( u = u_1 < \cdots < u_d \) be ordered variables. For a polynomial \( p \in \mathbb{Q}[u] \), denote by \( \text{factor}(p) \) the set of the non-constant irreducible factors of \( p \); for \( A \subset \mathbb{Q}[u] \), define \( \text{factor}(A) = \cup_{p \in A} \text{factor}(p) \). For a squarefree polynomial \( p \), the open projection operator (oproj) w.r.t. a variable \( v \in u \) is defined as below:
\[\text{oproj}(p, v) := \text{factor}(\text{discrim}(p, v)) \text{lc}(p, v)).\]
If \( p \) is not squarefree, then we define \( \text{oproj}(p, v) := \text{oproj}(p^*, v) \), where \( p^* \) is the squarefree part of \( p \); for a polynomial set \( A \), we define \( \text{oproj}(A, v) := \text{oproj}(\prod_{f \in A} f, v) \).

Given \( A \subset \mathbb{Q}[u] \) and \( x \in \{u_1, \ldots, u_d\} \), denote by \( \text{der}(A, x) \) the derivative closure of \( A \) w.r.t. \( x \). The open augmented projected factors of \( A \), denoted by \( \text{oaf}(A) \), is defined as follows. Let \( k \) be the smallest positive integer such that \( A \subset \mathbb{Q}[u_1, \ldots, u_k] \) holds. Let \( C = \text{factor}(\text{der}(A, u_k)) \); we have:

1. if \( k = 1 \), then \( \text{oaf}(A) := C \);
2. if \( k > 1 \), then \( \text{oaf}(A) := C \cup \text{oaf}(\text{oproj}(C, u_k)) \).

**3. BORDER POLYNOMIAL**

The relation “having the same saturated ideal” is an equivalence relation among regular chains of \( \mathbb{Q}[x] \). We show in this section that, for each equivalence class, there exists a unique representative whose border polynomial set is contained in the border polynomial set of any other representative.

To this end, we rely on the concept of canonical regular chain. In the field of triangular decompositions, several authors have used this term to refer to different notions. To be precise, we make use of the one defined in [13].

**Definition 1 (canonical regular chain).** Let \( T \) be a regular chain of \( \mathbb{Q}[x] \). If each polynomial \( t \) of \( T \) satisfies:

1. the initial of \( t \) involves only the free variables of \( T \),
2. for any polynomial \( f \) in \( T \) with \( \text{mvar}(f) < \text{mvar}(t) \), we have \( \deg(t, \text{mvar}(t)) < \text{mdeg}(f) \),

then we say that \( T \) is canonical.

**Remark 1.** Let \( T = \{t_1, \ldots, t_m\} \) be a regular chain; let \( d_k = \text{mdeg}(t_k) \), for \( k = 1 \cdots m \). One constructs a canonical regular chain \( T^* = \{t_1^*, t_2^*, \ldots, t_m^*\} \) such that \( \text{sat}(T) = \text{sat}(T^*) \) in the following way:

1. set \( t_1^* \) to be the primitive part of \( t_1 \) w.r.t. \( y_1 \);
2. for \( k = 2, \ldots, m \), let \( r_k \) be the iterated resultant
\[\text{res}(\text{init}(t_k), \{t_1, \ldots, t_{k-1}\}) \]
Suppose \( r_k = a_k \text{init}(t_k) + \sum_{i=1}^{k-1} c_i t_i \). Compute \( t \) as the pseudo-remainder of \( a_k t_k + \sum_{i=1}^{k-1} c_i t_i y_k \) by \( \{t_1^*, \ldots, t_{k-1}^*\} \). Set \( t_k^* \) to be the primitive part of \( t \) w.r.t. \( y_k \).

A canonical regular chain has the minimal border polynomial set among the family of regular chains having the same saturated ideal, which is stated in the following theorem.

**Theorem 1.** Given a squarefree regular chains \( T \) of \( \mathbb{Q}[x] \), there exists a unique canonical regular chain \( T^* \) such that \( \text{sat}(T) = \text{sat}(T^*) \). Moreover, we have \( \text{BP}(T^*) \subseteq \text{BP}(T) \).

The proof of the above theorem relies on some basic properties of border polynomial set recalled below.

Given a constructible set \( C \) defined by a parametric polynomial system, the minimal discriminant variety (MDV) [9]
of $C$, denoted by $mdv(C)$, is an intrinsic geometric object attached to $C$ and the parameters. The following results relate the border polynomial of a regular chain $T$ and the discriminant variety of the algebraic variety $V(T)$.

**Lemma 2** ([14]). Let $T$ be a squarefree regular chain of $\mathbb{Q}[u,y]$. Then we have $mdv(V(T)) = V(\prod_{f \in BP(T)} f)$.

**Lemma 3** ([14, Lemma 17]). Let $T$ be a squarefree regular chain of $\mathbb{Q}[u,y]$. Then we have $mdv(W(T)) \subseteq mdv(V(T))$ and $mdv(V(T)) \setminus mdv(W(T)) \subseteq V(\prod_{f \in B_{ini}(T)} f)$.

**Lemma 4.** Let $T_1$ and $T_2$ be squarefree regular chains of $\mathbb{Q}[x]$ such that $sat(T_1) = sat(T_2)$. If $B_{ini}(T_1) \subseteq B_{ini}(T_2)$, then we have $BP(T_1) \subseteq BP(T_2)$.

**Proof.** Firstly, we have $V(\prod_{f \in B_{ini}(T_2)} f) \subseteq mdv(V(T_1))$ by Lemma 2. Then with Lemma 3, we have $mdv(V(T_1)) = V(\prod_{f \in B_{ini}(T_2)} f) \cup mdv(W(T_1))$. Since $sat(T_1) = sat(T_2)$, we have $W(T_1) = W(T_2)$. Therefore, we have $mdv(V(T_2)) \subseteq mdv(V(T_1))$ by the assumption $B_{ini}(T_1) \subseteq B_{ini}(T_2)$, which implies the lemma.

Next we prove Theorem 1.

**Proof.** By Remark 1, we can always construct a canonical regular chain $T'$ such that $sat(T') = sat(T)$. Moreover, for each $t \in T$, we have $init(t')$ divides $res(init(t),T)$. Therefore, $B_{ini}(T') \subseteq B_{ini}(T)$ holds, which implies $BP(T') \subseteq BP(T)$ by Lemma 4.

Suppose $T''$ is any given canonical regular chain such that $sat(T'') = sat(T)$ holds. It is sufficient to show that $T'' \supseteq T''$ holds to complete the proof.

Note that $T''$, $T''$ and $T$ have the same set of free and algebraic variables, denoted respectively by $u$ and $y$. Given $I$ an ideal in $\mathbb{Q}[u,y]$, denote by $T'' ext$ the extension of $I$ in $\mathbb{Q}[u,y]$. Since $p^{ext} = 1$ holds for any prime ideal $p$ in $\mathbb{Q}[u,y]$ with $u$ algebraically dependent, we have $(T'')^{ext} = (T')^{ext}$ holds. Therefore, the polynomials in $T''$ (or $T''$) form a Gröbner basis of $sat(T')^{ext}$ (w.r.t. the lexicographical ordering on $y$) since their leading power products are pairwise coprime. Dividing each polynomial in $T''$ (or $T''$) by its initial, we obtain the unique reduced Gröbner basis of $sat(T')^{ext}$. This implies $T'' \supseteq T''$.

4. **Effective Boundary and FPS**

In this subsection, we will focus on an SFAS $\mathcal{S} = [T, P_r]$ in $\mathbb{Q}[u,y]$ where $u = u_1, \ldots, u_d$ are the free variables of $T$.

**Definition 2** (Effective Boundary). Let $h$ be a $(d-1)$-dimensional hypersurface in the parameter space $\mathbb{R}^d$ of $\mathcal{S}$. We call $h$ an effective boundary of $\mathcal{S}$ if for every hypersurface $H \not\subseteq h$ in $\mathbb{R}^d$, there exists a point $\ast \in h \setminus H$ satisfying: for any open ball $O(\ast)$ of $\ast$, there exist two points $\omega_1, \omega_2 \notin O(\ast) \setminus h$, s.t. $\#Z_{\mathcal{S}}(\omega_1) \neq \#Z_{\mathcal{S}}(\omega_2)$. Denote by $E(\mathcal{S})$ the union of all effective boundaries of $\mathcal{S}$.

Recall that the hypersurface defined by the border polynomial of an SFAS partitions the parameter space into regions, where the number of real solutions is locally invariant. One might imagine that the effective boundaries are strongly related to the border polynomial set. Indeed, we have the following Lemma stating the relation.

**Lemma 5.** We have $E(\mathcal{S}) \subseteq Z_R(\prod_{f \in BP(\mathcal{S})} f = 0)$.

**Proof.** Let $h \in E(\mathcal{S})$ such that $h \not\subseteq Z_R(\prod_{f \in BP(\mathcal{S})} f = 0)$ holds. Then for each $u \in h \setminus Z_R(\prod_{f \in BP(\mathcal{S})} f = 0)$, we can choose an open ball $O(u)$ of $u$ contained in a connected component of the set $Z_R(\prod_{f \in BP(\mathcal{S})} f = 0)$. By Lemma 1, for any two points $\alpha_1, \alpha_2 \in O(u)$, $\#Z_R(\mathcal{S}(\alpha_1)) = \#Z_R(\mathcal{S}(\alpha_2))$ holds. That is a contradiction to the assumption of $h$ being an effective boundary.

Lemma 5 implies that the set of effective boundaries represented by irreducible polynomials of $\mathbb{Q}[u]$ is finite and can be given by polynomials from the border polynomial set.

**Definition 3.** A polynomial $p$ in BP($\mathcal{S}$) is called an effective border polynomial factor if $Z_R(p = 0)$ is an effective boundary of $\mathcal{S}$. We denote by $ebf(\mathcal{S})$ the set of effective border polynomial factors.

The example below shows that some of the polynomials in a border polynomial may not be effective. Roughly speaking, the factors in $B_{ini}$ are not effective. This property is formally stated in a soon coming extended version of this article.

**Example 1.** Consider an SFAS $R = \{ax^2 + bx + 1\}$. Its border polynomial set is $\{a, b^2 - 4a\}$. One can verify from Figure 1 that $Z_R(b^2 - 4a = 0)$ is an effective boundary of $R$, while $Z_R(a = 0)$ is not. Indeed, all $a, b$-values in the blank (resp. filled) area specialize $R$ to have 2 (resp. 0) real solutions.

**Figure 1: Effective and non-effective boundary**
THEOREM 2. A polynomial \( p \) in \( BP(E) \) is an effective border polynomial factor if and only if there exist two connected components \( C_1, C_2 \) of \( Z \) such that \( Z(p = 0) \) is of dimension \( d - 1 \),

(1) \( \partial C_1 \cap \partial C_2 \cap Z(p = 0) \) is of dimension \( d - 1 \),
(2) for all point \( \alpha_1 \in C_1 \) and for all point \( \alpha_2 \in C_2 \) we have \( \#Z(K(\alpha_1)) \neq \#Z(K(\alpha_2)) \).

Proof. "\( \Rightarrow \)." Suppose \( p \) is an effective border polynomial factor. By definition, there exists a point \( u^* \in Z(p = 0) \) such that \( Z(p = 0) \) is a connected open ball centered at \( u^* \) satisfying the properties below:

(i) \( O(u^*) \setminus Z(p = 0) \subseteq Z(p = 0) \),
(ii) \( O(u^*) \cap Z(p = 0) \subseteq Z(p = 0) \),
(iii) there exist two points \( \alpha_1, \alpha_2 \in Z(p = 0) \), such that \( \#Z(K(\alpha_1)) \neq \#Z(K(\alpha_2)) \).

Property (iv) can be achieved by imposing that \( Z(p = 0) \) is not singular at \( u^* \). Property (iv) and Lemma 1 imply that \( O(u^*) \setminus Z(p = 0) \) is a connected set. Since \( O(u^*) \) is an open ball, we deduce that \( O(u^*) \setminus Z(p = 0) \) must be 0-dimensional. Therefore, Property (iv) implies \( O(u^*) \cap Z(p = 0) = O(u^*) \cap C_1 \cup O(u^*) \cap C_2 \), for \( i = 1, 2 \). Therefore, we have: \( O(u^*) \cap Z(p = 0) \subseteq (\partial C_1 \cap \partial C_2) \cap Z(p = 0) \). Hence \( (\partial C_1 \cap \partial C_2) \cap Z(p = 0) \) is also of dimension \( d - 1 \).

"\( \Leftarrow \)." Suppose there exist two connected components \( C_1, C_2 \) of \( Z(p = 0) \) satisfying the above (1) and (2) in the theorem statement. Let \( H \) be a hypersurface with \( H \not\subseteq Z(p = 0) \). Since the dimension of \( (H \cup Z(p = 0)) \cap Z(p = 0) \) cannot be \( d - 1 \), the set \( S \) defined by

\[
(\partial C_1 \cap \partial C_2 \cap Z(p = 0)) \setminus \left( \left( H \cup Z(p = 0) \right) \setminus \left( \bigcup_{f \in BP(E)} f = 0 \right) \right)
\]

is not empty. Let \( u^* \) be a point of \( S \). Any open ball \( O(u^*) \) centered at \( u^* \) contains at least one point \( \alpha_1 \) (resp. \( \alpha_2 \)) from \( C_1 \) (resp. \( C_2 \)). From (2) we deduce \( \#Z(K(\alpha_1)) \neq \#Z(K(\alpha_2)) \). That is, \( Z(p = 0) \) is an effective boundary according to Definition 2.

The above theorem suggests some practical ways to compute the effective border polynomial factors, using the adjacency information and sample points of the connected components of \( Z(p = 0) \).

COROLLARY 1. If two points \( \alpha_1, \alpha_2 \in Z(p = 0) \) are in the same connected component of the complement of \( E(\alpha_1) \), then \( \#Z(K(\alpha_1)) = \#Z(K(\alpha_2)) \).

Proof. Let \( C \) be a connected component of the complement of \( E(\alpha_1) \). Observe that \( C \setminus Z(p = 0) \) is the union of a finite set \( O \) of connected components of \( Z(p = 0) \). Indeed, \( E(\alpha_1) \subseteq Z(p = 0) \) is open.

Assume from now that \( O \) contains more than one element. We can number the elements of \( O \) such that for any two elements with consecutive numbers, say \( \alpha_i, \alpha_{i+1} \), the dimension of \( \partial C_1 \cap \partial C_1 \) is \( d - 1 \). Proceeding by contradiction, assume that the conclusion of the corollary is false. Thus, there exist two consecutive elements of \( O \), say \( \alpha_i, \alpha_{i+1} \), and two points \( \alpha_i \in C_i, \alpha_{i+1} \in C_{i+1} \) such that \( \#Z(K(\alpha_i)) \neq \#Z(K(\alpha_{i+1})) \). Since \( C \) lies in the complement of \( E(\alpha_1) \), there exists a non-effective border polynomial factor \( p \) such that \( \partial C_1 \cap \partial C_{i+1} \subseteq Z(p = 0) \). However, this also implies that \( p \) is an effective border polynomial factor by Theorem 2, which is a contradiction.

Given a pre-regular system \( R = [B_\eta, T, P]_\eta \), we can rely on \( ebf([T, P]) \) to compute an FFS of \( R \) rather than \( B \) (which is often much larger than \( ebf([T, P]) \)).

THEOREM 3. Given a pre-regular system \( R = [B_\eta, T, P]_\eta \), let \( D = \alpha ebf([T, P]) \). Then \( D \cup B \) is an FFS of \( R \).

Proof. By Theorem 3 in [3] on the property of the oaf operator, each realizable strict sign conditions on \( D \) defines a connected components of \( Z(p = 0) \). Therefore, for any two points \( \alpha_1, \alpha_2 \in Z(p = 0) \) satisfying the same realizable sign condition of \( D \), we have \( \#Z(K(\alpha_1)) = \#Z(K(\alpha_2)) \) by Corollary 1. Hence \( D \cup B \) is an FFS of \( R \) by definition.

THEOREM 4. Given two SFSAs \( R_1 = [T_1, P_1]_1 \) and \( R_2 = [T_2, P_2]_2 \) with \( sat(T_1) = sat(T_2) \), then \( ebf(R_1) = ebf(R_2) \).

Proof. Let \( B = BP(R_1) \cup BP(R_2) \) and let \( h \) be an effective boundary of \( R_1 \) defined by a polynomial \( p \) in \( BP(R_1) \). Let \( H \not\subseteq h \) be any hypersurface and denote by \( S \) the set \( \left( Z(p = 0) \setminus \left( \bigcup_{f \in BP(E)} f = 0 \right) \right) \). Observe that \( S \) is not empty.

We can find a point \( u^* \in S \) satisfying: for any open ball \( O(u^*) \) centered at \( u^* \), there exist two points \( \alpha_1, \alpha_2 \in O(u^*) \) such that \( \#Z(K(\alpha_1)) \neq \#Z(K(\alpha_2)) \).

Since \( sat(T_1) = sat(T_2) \), for all \( u \in Z(p = 0) \), we have \( Z(R_1(u)) = Z(R_2(u)) \). When an open ball \( O \) at \( u^* \) is sufficiently small, \( O \cap Z(p = 0) \subseteq \emptyset \). Therefore, \( Z(R_1(u)) = Z(R_2(u)) \) holds for any \( u \in O \).

From the above arguments and Definition 2, we deduce that \( h \) is also an effective boundary of \( R_2 \). This shows \( ebf(R_1) \subseteq ebf(R_2) \). Similarly \( ebf(R_1) \subseteq ebf(R_2) \) can be proved.

Let \( R = [T, P]_\eta, R_i = [T_i, P_i]_i \) be three SFSAs with \( sat(T) \cap sat(T_2) \). One can prove that \( ebf(R) \subseteq ebf(R_1) \cup ebf(R_2) \). Moreover, one can prove that \( ebf(R_1) \cap ebf(R_2) = \emptyset \) implies \( ebf(R) = ebf(R_1) \cup ebf(R_2) \). These results and their proofs will appear in an extended version of this article.
5. RELAXATION TECHNIQUES

Given a pre-regular semi-algebraic system $R = \{B_\sigma, T, P_\sigma\}$ as input, the algorithm $\text{GenerateRegular\text{S}}\_\text{Sas}$ in [3] generates an FPS $\mathbf{F} \supseteq B$ of $R$ and a regular semi-algebraic system $[Q, T, P_\sigma]$ such that $Z_b(\mathbf{F}_2) \cap Z_b(R) = Z_b([Q, T, P_\sigma])$. Denote by $B^*$ the polynomial set $\text{oa}(B)$, which is proved to be an FPS of $R$ by Theorem 4 in [3]. The notations $R$, $B$, $T$, $P$, $\mathbf{F}$, $B^*$ will be fixed in this section.

Note that if $\mathbf{F} = B$, then we have $Z_b(R) = Z_b([Q, T, P_\sigma])$; otherwise, for each $b \in \mathbf{F} \setminus B$, we have to compute recursively a triangular decomposition of $[T \cup \{b\}, \{P_\sigma, B_\sigma\}]$ to obtain a complete triangular decomposition of $R$. There are two directions to reduce the number of such recursive calls, which will help to produce output with less redundancy:

(i) minimize the number of polynomials in $\mathbf{F}$, where the effective boundary theory in Section 4 can help;
(ii) relax some polynomials in $\mathbf{F} \setminus B$ such that there is no need to make recursive calls for those polynomials, which we will discuss in this section.

The following notions of sign condition and relaxation appear in [1] in a more general setting. We adapt them to our study of regular semi-algebraic systems. Throughout this subsection, we consider a finite set $F \subseteq \mathbb{Q}[x]$ of coprime polynomials.

**Definition 4.** We call any semi-algebraic system of the form

$$\bigwedge_{f \in \mathbf{F}} f \sigma_f 0,$$

where $\sigma_f$ is one of $>, \leq$, a sign condition on $F$, or an F-sign condition. An F-sign condition is called strict if every $\sigma_f$ involved belongs to $\{>, \leq\}$. An F-sign condition $C$ is called realizable if $C$ has at least one real solution.

**Definition 5.** (Relaxation of sign condition). For an F-sign condition $C$ given as in (1) and a subset $E$ of $F$, the (partial) relaxation of $C$ w.r.t. $E$, denoted by $\overline{C}_E$, is defined by

$$\bigwedge_{p \in \mathbf{F}} p \overline{\sigma}_p 0\text{ where } \overline{\sigma}_p = \begin{cases} <, & \text{if } p \in E \text{ and } \sigma_p <, \\ \geq, & \text{if } p \in E \text{ and } \sigma_p >, \\ \sigma_p, & \text{otherwise.} \end{cases}$$

Let $C = \bigwedge_{f \in \mathbf{F}} f \sigma_f 0$, where $\sigma_f \in \{>, \leq\}$ if $f \in F$ and $\sigma_f \in \{>, \leq\}$ if $f \in \mathbf{F} \setminus D$. Moreover, assume that for any $u$ such that $D(u) \neq 0$, $R(u)$ has (resp. has no) real solutions if and only if $Q(u)$ (resp. $Q_0(u)$) is true. Let $h$ be a polynomial in $D \setminus B$. Denote by $D^h$ the set $D \setminus \{h\}$. Denote by $\partial_i$ ($i = 0, 1$) the boundary of the set $Z_b(Q_i)$. Denote by $G_i$ ($i = 0, 1$) the set $Z_b(Q_i) \cap Z_b(Q_0)$. Let $S_i$ ($i = 0, 1$) be the semi-algebraic set such that $Z_b(Q_i) = G_i \cup S_i$, where the symbol $\cup$ denotes disjoint union.

The following Theorem states an criterion for relaxation.

**Theorem 5.** The following two statements are equivalent:

(i) $Z_b(Q_1) \cap Z_b(Q_0) = \emptyset$,
(ii) for any $u \in Z_b(D^h)$, $R(u)$ has real solutions if and only if $\overline{Q}_1(u)$ is true; $R(u)$ has no real solutions if and only if $\overline{Q}_0(u)$ is true.

Before providing the proof, we supply several lemmas on the properties of the objects we defined.

**Lemma 6.** $Z_b(Q_0)$ and $Z_b(Q_1)$ are both open sets.
Proof. On one hand, \( Z_h(D_\delta) = Z_h(Q_0) \cup Z_h(Q_1) \). On the other hand, there exists a finite set of connected open sets, \( O = \{ C_1, \ldots, C_n \} \), such that \( Z_h(D_\delta) = \bigcup_{i=1}^n C_i \) holds. By Lemma 1, for each \( C_i \in O \), either \( C_i \subseteq Z_h(Q_0) \) or \( C_i \subseteq Z_h(Q_1) \) holds. Therefore, both \( Z_h(Q_0) \) and \( Z_h(Q_1) \) are a union of finitely many elements of \( O \) and thus are open.

Lemma 7. For any \( u \in Z_h(Q_0) \cap Z_h(B_\delta) \), \( R(u) \) has no real solutions; for any \( u \in Z_h(Q_1) \cap Z_h(B_\delta) \), \( R(u) \) has real solutions.

Proof. Suppose \( u \in Z_h(Q_0) \cap Z_h(B_\delta) \). There exists a connected component \( C \) of \( Z_h(Q_0) \) and a connected component \( C' \) of \( Z_h(B_\delta) \) such that \( u \in C \cap Z_h(B_\delta) \subseteq C' \) holds. Since \( C \subseteq Z_h(Q_0) \subseteq Z_h(B_\delta) \), we have \( C \subseteq C' \). Since the number of real solutions of \( R \) is constant above \( C' \) (by Lemma 1) and \( R \) has no real solutions above \( C \), we conclude that \( R(u) \) has no real solutions. The other part of the lemma can be proved similarly.

Note that \( G_i = Z_h(\tilde{Q}^h_i) \cap Z_h(B_\delta) \subseteq Z_h(B_\delta) \cap Z_h(Q_1) \) \((i = 0, 1)\) holds. We have the following proposition as a direct consequence of Lemma 7.

Proposition 1. For any \( u \in G_0 \), \( R(u) \) has no real solutions; for any \( u \in G_1 \), \( R(u) \) has real solutions.

Lemma 8. The following relations hold: \( (i) \) \( \partial_0 \cup \partial_1 = Z_h(\prod_{f \in D \bar{f}}) \); \( (ii) \) \( \partial_0 \cap \partial_1 \subseteq Z_h(\prod_{f \in D \bar{f}}) \).

Proof. By Lemma 6, both \( Z_h(Q_0) \) and \( Z_h(Q_1) \) are open sets. We have \( \partial_0 \cup \partial_1 = \partial(Z_h(Q_0) \cup Z_h(Q_1)) \), since \( Z_h(Q_0) \cap Z_h(Q_1) = \emptyset \) holds. Therefore, we have
\[
\partial_0 \cup \partial_1 = \overline{Z_h(Q_0) \cup Z_h(Q_1)} \setminus (Z_h(Q_0) \cup Z_h(Q_1)) = Z_h(D^\delta) \setminus (Z_h(Q_1)) = Z_h(\prod_{f \in D \bar{f}}).
\]

By Lemma 7, \( Z_h(Q_0) \cap Z_h(B_\delta) \) and \( Z_h(Q_1) \cap Z_h(B_\delta) \) have no intersection. Therefore \( Z_h(Q_0) \cap Z_h(Q_1) \cap Z_h(B_\delta) = \emptyset \). Then the conclusion follows by \( \partial_0 \subseteq Z_h(Q_1) \) \((i = 0, 1)\).

Lemma 9. The following relations hold: \( (a) \) for \( i = 0, 1 \), \( Z_h(Q_i') \cap Z_h(D^\delta_h) \subseteq Z_h(\tilde{Q}^h_i) \); \( (b) \) \( Z_h(Q_0') \cup Z_h(\tilde{Q}^h_1) = Z_h(D^\delta_h) \).

Proof. Since \( Z_h(D^\delta_h) \) is a closed set, we have \( Z_h(Q_1') \subseteq Z_h(\tilde{Q}^h_1) \). Therefore, we have \( Z_h(D^\delta_h) \cap Z_h(Q_i') \subseteq Z_h(D^\delta_h) \cap Z_h(\tilde{Q}^h_i) = Z_h(\tilde{Q}^h_i) \).

By \((a)\), we have \( Z_h(D^\delta_h) \cap (U_{i=0,1} Z_h(Q_i')) \subseteq U_{i=0,1} Z_h(\tilde{Q}^h_i) \), which implies that \( Z_h(D^\delta_h) \subseteq Z_h(\tilde{Q}^h_i) \cup Z_h(\tilde{Q}^h_1) \). And \( Z_h(Q_0') \cup Z_h(Q_1') \subseteq Z_h(D^\delta_h) \) holds since all polynomials in \( D^h \) remain strict after relaxing \( h \).

Proposition 2. For \( i = 0, 1 \), we have \( S_i \subseteq Z_h(h = 0) \cap Z_h(\tilde{Q}^h_i) \) holds.

Proof. Recall that \( G_i = Z_h(\tilde{Q}^h_i) \cap Z_h(Q_i) \), \( Z_h(\tilde{Q}^h_i) = G_i \cup S_i \). Therefore, we have \( Z_h(Q_i) \subseteq G_i \) and \( S_i = Z_h(\tilde{Q}^h_i) \setminus G_i \subseteq Z_h(\tilde{Q}^h_i) \cup Z_h(Q_i) \subseteq Z_h(h = 0) \) hold. Hence, we deduce that \( S_i \subseteq Z_h(h = 0) \cap Z_h(\tilde{Q}^h_i) \) holds.

Lemma 10. Both \( S_i \subseteq G_0 \) and \( S_0 \subseteq G_1 \) hold.

Proof. By Lemma 8, we have \( \partial_0 \cup \partial_1 = Z_h(\prod_{f \in D \bar{f}}) \setminus \emptyset \). Since \( h \in D \), we have \( Z_h(h = 0) \subseteq \partial_0 \cup \partial_1 \), which implies \( Z_h(h = 0) \) can be rewritten as \( Z_h(h = 0) \cap ((\partial_0 \setminus \partial_1) \cup (\partial_1 \setminus \partial_0) \cup (\partial_0 \cap \partial_1)) \).

By Lemma 8, we have \( \partial_0 \cap \partial_1 \subseteq Z_h(\prod_{f \in D \bar{f}}) \setminus \emptyset \), which implies that \( Z_h(D^\delta_h) \cap \partial_0 \cap \partial_1 \subseteq \emptyset \). Let \( S_h \) be \( Z_h(h = 0) \cap Z_h(D^\delta_h) \). Then \( S_h \) can be rewritten as \( (Z_h(h = 0) \cap Z_h(D^\delta_h) \cap (\partial_0 \setminus \partial_1) \cup (Z_h(h = 0) \cap Z_h(D^\delta_h) \cap (\partial_1 \setminus \partial_0)) \).

Intersecting both sides of relation \( (a) \) of Lemma 9 with \( Z_h(Q_i) \), we obtain \( Z_h(D^\delta_h) \cap Z_h(Q_i) \subseteq G_i \), which implies that \( Z_h(D^\delta_h) \cap \partial_i \subseteq G_i \). Therefore, \( S_h \subseteq G_0 \cup G_1 \) holds.

Since \( Z_h(\tilde{Q}^h_i) \subseteq Z_h(D^\delta_h) \), we have \( Z_h(h = 0) \cap Z_h(\tilde{Q}^h_i) \subseteq S_h \). By Proposition 2, we have \( S_i \subseteq Z_h(h = 0) \cap Z_h(\tilde{Q}^h_i) \). Therefore, \( S_i \subseteq S_h \) holds.

We then deduce the conclusion by combining the facts \( S_i \cap G_i = \emptyset \), \( S_i \subseteq S_h \), and \( S_h \subseteq G_0 \cup G_1 \).

Corollary 2. We have \( Z_h(\tilde{Q}^h_1) \cap Z_h(\tilde{Q}^h_0) = S_0 \cup S_1 \).

Proof. We can rewrite \( Z_h(\tilde{Q}^h_1) \cap Z_h(\tilde{Q}^h_0) \) as the disjoint union \((S_1 \cap G_0) \cup (S_0 \cap G_1) \cup (S_1 \cap S_0) \cup (G_0 \cap G_1) \). By Proposition 1, \( G_0 \cap G_1 = \emptyset \). Together with Lemma 10, we have \( Z_h(\tilde{Q}^h_1) \cap Z_h(\tilde{Q}^h_0) = S_0 \cup S_1 \).

Next, we complete the proof for Theorem 5.

Proof. By Lemma 9, \( Z_h(\tilde{Q}^h_0) \cup Z_h(\tilde{Q}^h_1) = Z_h(D^\delta_h) \).

(i) \( \Rightarrow \) (ii). By Corollary 2, we have \( S_0 = S_1 = \emptyset \) and \( Z_h(\tilde{Q}^h_i) = G_i \) \((i = 0, 1)\). Then the conclusion follows from Proposition 1.

(ii) \( \Rightarrow \) (i). We prove by contradiction. Assume (i) does not hold. There exists \( u \in Z_h(D^\delta_h) \), such that both \( \tilde{Q}^h_i(u) \) and \( \tilde{Q}^h_i(u) \) are true. This is a contradiction to (ii).

We have the following remarks on relaxation once (i) of Theorem 5 is checked to be true.
• One can verify that $\tilde{Q}_i^h$ ($i = 0, 1$) and $D^h$ have the same configuration as that we assumed on $Q_i$, ($i = 0, 1$) and $D$. So $Z_k(\tilde{Q}_i^h)$ is still open by Lemma 6.

• If $[Q_i, T, P_i]$ is a regular semi-algebraic system, then so is $[\tilde{Q}_i^h, T, P_i]$.

6. INCREMENTAL DECOMPOSITION

In this section, we present algorithms to compute a full triangular decomposition of a semi-algebraic system in an incremental manner, which serves as a counterpart of the recursive algorithm in our previous paper [3]. Given a semi-algebraic system $\mathcal{S} := [F, N_2, P_2, H_\varphi]$, the incremental decomposition is realized by passing the empty regular chain $\emptyset$ and $\mathcal{S}$ to Algorithm 1, whose incrementality is mainly due to its subroutine Triangularize, which computes a Lazard triangular decomposition by solving equations one by one [11].

External algorithms. We recall the specifications of the algorithms BorderPolygonalSet and GenerateRegularSas, (see [3]), Triangularize, Intersect, RegularOnly (see [11]). BorderPolygonalSet computes the border polynomial set of a regular system, whereas GenerateRegularSas decomposes the zero set of a pre-regular semi-algebraic system as a union of zero sets of regular semi-algebraic systems. Let $p$ be a polynomial, $F$ be a polynomial list, and $T$ be a regular chain. The algorithm Triangularize($F, T, \text{mode} = \text{Lazard}$) computes regular chains $T_i$, $i = 1, \ldots, e$, such that $V(F) \cap W(T) \subseteq \bigcup_{i=1}^e W(T_i) \subseteq V(F) \cap W(T)$. The algorithm Intersect($p, T$) is equivalent to Triangularize($\{p\}, T, \text{mode} = \text{Lazard}$). The algorithm RegularOnly($T, F$) computes regular chains $T_i$, $i = 1, \ldots, e$, such that $W(F) \cap W(T_i) = W(T_i) \setminus \bigcup_{i' \in \bar{F}} H_i$ and every polynomial in $F$ is regular modulo sat($T_i$).

The proof of the termination and correctness of the algorithms rely on standard arguments used in the proof of algorithm PCTD in paper [4]. Limited to space, we will not expand the proof here.

Algorithm 1: RealTriangularize($T, F, N_2, P_2, H_\varphi$)

Input: a regular chain $T$ and a semi-algebraic system $\mathcal{S} := [F, N_2, P_2, H_\varphi]$ and $D$.
Output: a set of regular semi-algebraic systems $R_i$, $i = 1, \ldots, e$, such that $W_k(T) \cap Z_k(\mathcal{S}) = \bigcup_{i=1}^e Z_k(R_i)$.

\begin{align*}
\mathcal{T} &:= \text{Triangularize}(F, T, \text{mode} = \text{Lazard}); \\
\text{for } C \in \mathcal{T} \text{ do} &\phantom{;} \text{output RealTriangularize} (C, N_2, P_2, H_\varphi \cup \text{init}(T)_{\varphi});
\end{align*}

7. SET THEORETICAL OPERATIONS

In paper [3], we proved that every semi-algebraic set can be represented by the union of zero sets of finitely many regular semi-algebraic systems. It is natural to ask how to perform set theoretical operations, such as union, intersection, complement and difference of semi-algebraic sets based on such a representation.

Note that each (regular) semi-algebraic system can also be seen as a quantifier free formula. So one can implement the set operations naively based on the algorithm RealTriangularize and logic operations. However, an obvious drawback of such an implementation is that it totally neglects the structure of a regular semi-algebraic system.

Indeed, if the structure of the computed object can be exploited, it is possible to obtain more efficient algorithms. One good example of this is the Difference algorithm, which computes the difference of zero sets of two regular systems, presented in [6]. This algorithm exploits the structure of a regular chain and outperforms the naive implementation by several orders of magnitude.

Apart from the algebraic computations, the idea behind the Difference algorithm of paper [6] is to compute the difference $(A_1 \cap A_2) \setminus (B_1 \cap B_2)$ in the following way:

$$(A_1 \cap B_1) \cap (A_2 \setminus B_2) \cup (A_2 \cap B_1) \cap A_2.$$ 

Observe that if $A_1 \cap B_1 = \emptyset$, then the difference is $(A_1 \cap A_2)$. Moreover, computing $\cap_{s, t \geq 2}$ can be reduced to the above base case.

In this section, we present algorithms (Algorithm 4 and 5) which take advantage of the algorithm Difference (also an algorithm Intersection derived from it) and the idea presented above for computing the intersection and difference of semi-algebraic sets represented by regular semi-algebraic systems.

Algorithm 2: RealTriangularize($T, N_2, P_2, H_\varphi$)

Input: a regular chain $T$ and a semi-algebraic system $\mathcal{S} := [F, N_2, P_2, H_\varphi]$.
Output: a set of regular semi-algebraic systems $R_i$, $i = 1, \ldots, e$, such that $W_k(T) \cap Z_k(\mathcal{S}) = \bigcup_{i=1}^e Z_k(R_i)$.

\begin{align*}
H &:= \text{init}(T) \cup H; \\
\mathcal{T} &:= \{\emptyset\}; \quad \mathcal{T}' := \emptyset; \\
\text{for } p \in N \text{ do} &\phantom{;} \text{for } (T', N') \in \mathcal{T} \text{ do} \phantom{;} \text{output RealTriangularize} (T', N', P_2, H_\varphi \cup \text{init}(T)_{\varphi}); \\
\text{for } C \in \mathcal{T} \text{ do} &\phantom{;} \text{output RealTriangularize} (C, N_2, P_2, H_\varphi \cup \text{init}(T)_{\varphi});
\end{align*}

8. EXPERIMENTATION

In this section, we report on the experimental results of the techniques presented in this paper. The systems were tested...


**Algorithm 4: DifferenceRsas(R, R')**

**Input:** two regular semi-algebraic systems $R = [Q, T, P_s]$ and $R' = [Q', T', P'_s]$

**Output:** a set of regular semi-algebraic systems $R_i$, $i = 1, \ldots, e$, such that $Z_{\delta}(R) \setminus Z_{\delta}(R') = \bigcup_{i=1}^{e} Z_{\delta}(R_i)$.

begin
\[ Q' := Q \wedge P_s; \]
\[ Q'' := Q' \wedge P'_s; \]
\[ \mathcal{T} := \text{Difference}(T, T'); \]
\[ \mathcal{T}'' := \text{Intersection}(T, T'); \]
if $\mathcal{T}'' = \emptyset$ then return $R$; 
for $[T^*, H^*] \in \mathcal{T}''$ do
\[ Q^* = Q \setminus Q' \wedge H''_s; \]
\[ \text{output RealTriangularize}(T^*, Q^*) \]
for $[T^*, H^*] \in \mathcal{T}$ do
\[ Q^* = Q \wedge H''_s; \]
\[ \text{output RealTriangularize}(T^*, Q^*) \]

**Algorithm 5: IntersectionRsas(R, R')**

**Input:** two regular semi-algebraic systems $R = [Q, T, P_s]$ and $R' = [Q', T', P'_s]$

**Output:** a set of regular semi-algebraic systems $R_i$, $i = 1, \ldots, e$, such that $Z_{\delta}(R) \cap Z_{\delta}(R') = \bigcup_{i=1}^{e} Z_{\delta}(R_i)$.

\[ Q'' := Q \wedge P_s \wedge Q' \wedge P'_s; \]
for $[T^*, H^*] \in \text{Intersection}(T, T')$ do 
\[ \text{output RealTriangularize}(T^*, Q'' \wedge H''_s) \]

on a machine with Intel Core 2 Quad CPU (2.40GHz) and 3.0Gb total memory. The time-out is set as 3600 seconds. The memory usage is limited to 60% of total memory. NA means the computation does not finish in the resource (time or memory) limit.

In Table 1, RTD denotes RealTriangularize. The subscripts re and inc denote respectively the recursive and incremental implementation of RealTriangularize. The suffixes +relax and -relax denote respectively applying and not applying relaxation techniques. The name RR, short name for RemoveRedundantComponents, is an algorithm, implemented based on the algorithm DifferenceRsas, to remove the redundant components in the output of RTD. For each algorithm, the left column records the time (in seconds) while the right one records the number of components in the output.

Table 1 illustrates the effectiveness of the techniques presented in this paper. For system 8-3-config-Li, RTD[inc] greatly outperforms RTD[re]. Moreover, RR helps reduce the number of the output components of RTD[re] from 203 to 45. For system Metha0, with the relaxation technique, both timing and the number of components in the output are reduced. For system SEIT, with the help of relaxation, RTD[re] can now solve it within half an hour.

To conclude, the algorithms of [3] can, in practice, be often substantially improved by better analysis of the border polynomials, by relaxation (where allowed) and by the incremental approach. The experimentation shows that the latter can sometimes result in a speed-up by more than 10.

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**9. ADDITIONAL AUTHORS**

**10. REFERENCES**


