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# An Easy Algorithm For The General Vector Addition System Reachability Problem

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## ABSTRACT

The reachability problem for Vector Addition Systems (VAS) or equivalently for Petri Nets is a central problem of net theory. The general problem is known decidable by algorithms exclusively based on the classical Kosaraju-Lambert-Mayr-Sacerdote-Tenney (KLMST) decomposition. This decomposition is difficult and it just has a non-primitive recursive upper-bound complexity. In this paper, we prove that if a configuration is not reachable from an initial configuration, there exists a semi-linear inductive invariant that proves this property. We deduce an easy algorithm for deciding the reachability problem based on two semi-algorithms. A first one that tries to prove the reachability by fairly enumerating the possible paths and a second one that tries to prove the non-reachability by fairly enumerating semi-linear inductive invariants. This algorithm is the very first one that does not require the KLMST decomposition. In particular, this algorithm is the first candidate to obtain a precise (eventually elementary) upper-bound complexity for the VAS reachability problem.

## 1. INTRODUCTION

Vector Addition Systems (VAS) or equivalently Petri Nets are one of the most popular formal methods for the representation and the analysis of parallel processes [2]. The reachability problem is central since many computational problems (even outside the parallel processes) reduce to the reachability problem. Sacerdote and Tenney provided in [10] a partial proof of the decidability of this problem. The proof was completed in 1981 by Mayr [9] and simplified by Kosaraju [7] from [10, 9]. Ten years later [8], Lambert provided a more simplified version based on [7]. This last proof still remains difficult and the upper-bound complexity of the corresponding algorithm is just known non-primitive recursive. Nowadays, the exact complexity of the reachability problem for VAS is still an open-problem. Even an elementary upper-bound complexity is open. In fact, the known general reachability algorithms are exclusively based on the Kosaraju-Lambert-Mayr-Sacerdote-Tenney (KLMST) decomposition.

In this paper, we prove that if a configuration is not reachable from an initial configuration, there exists a semi-linear set or equivalently a formula in the Presburger arithmetic [3] that denotes an inductive invariant proving this property. We deduce an easy algorithm for deciding the reachability problem based on two semi-algorithms. A first one that tries to prove the reachability by fairly enumerating the possible paths and a second one that tries to prove the non-reachability by fairly enumerating semi-linear inductive invariants. This algorithm is the very first one that does not require the KLMST decomposition. In particular, this algorithm should be a good candidate to obtain a precise (eventually elementary) upper-bound complexity for the VAS reachability problem. Note [5] that in general, reachability sets are not semi-linear. Semi-linear inductive invariants are obtained by over-approximating reachability sets by semi-linear sets. In fact, we observe that reachability sets can be precisely over-approximated by semi-linear sets.

*Outline of the paper:* In section 2, the non-reachability problem for VAS is reduced to the existence of separators (a pair of inductive invariants). In section 3 we introduce the class of semi-pseudo-linear sets, a class of sets that can be precisely over-approximated by semi-linear sets. In section 4, reachability sets are proved semi-pseudo-linear. Finally in section 5 we show the existence of semi-linear separators proving the non-reachability of a pair of configurations. *In order to simplify the presentation of this paper, the independent parts of sections 3 and 4 with the remaining of the*

paper are presented in some sub-sections. That means the reader may safely skip these sub-sections in order to read other sections of the paper.

## 2. VECTOR ADDITION SYSTEMS

In this section, the non-reachability problem for Vector Addition Systems is reduced to the existence of *separators*.

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1 Reachability ( $\mathbf{s} \in \mathbb{N}^n$ ,  $\mathcal{V} = (\Sigma, n, T)$  a VAS,  $\mathbf{s}' \in \mathbb{N}^n$ )
2   repeat forever
3     fairly select  $\sigma \in \Sigma^*$ 
4     if  $\mathbf{s} \xrightarrow{\sigma}_{\mathcal{V}} \mathbf{s}'$ 
5       return "reachable"
6     fairly select  $(\psi(\mathbf{x}), \psi'(\mathbf{x}))$  formulas in  $\text{FO}(\mathbb{N}, +, \leq)$ 
7     if  $(\psi(\mathbf{x}), \psi'(\mathbf{x}))$  denotes separator for  $(\{\mathbf{s}\}, \{\mathbf{s}'\})$ 
8       return "unreachable"

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*Some notations* : As usual we denote by  $\mathbb{Q}, \mathbb{Q}_+, \mathbb{Z}, \mathbb{N}$  respectively the set of rational values, non-negative rational values, the set of integers and the set of non-negative integers. The components of a vector  $\mathbf{x} \in \mathbb{Q}^n$  are denoted by  $(\mathbf{x}[1], \dots, \mathbf{x}[n])$ . Given a function  $f : E \rightarrow F$  where  $E, F$  are sets, we denote by  $f(X) = \{f(x) \mid x \in X\}$  for any subset  $X \subseteq E$ . This definition naturally defines sets  $X_1 + X_2$  where  $X_1, X_2 \subseteq \mathbb{Q}^n$ . With slightly abusing notations,  $\{\mathbf{x}_1\} + X_2$  and  $X_1 + \{\mathbf{x}_2\}$  are simply denoted by  $\mathbf{x}_1 + X_2$  and  $X_1 + \mathbf{x}_2$ . The total order  $\leq$  over  $\mathbb{Q}$  is extended component-wise to the partial order  $\leq$  satisfying  $\mathbf{x} \leq \mathbf{x}'$  if and only if  $\mathbf{x}[i] \leq \mathbf{x}'[i]$  for any  $1 \leq i \leq n$ . The set of minimal elements for  $\leq$  of a set  $X \subseteq \mathbb{N}^n$  is denoted by  $\min(X)$ . As  $(\mathbb{N}^n, \leq)$  is well partially ordered set, recall that  $\min(X)$  is finite and  $X \subseteq \min(X) + \mathbb{N}^n$  for any  $X \subseteq \mathbb{N}^n$ .

A *Vector Addition System* (VAS) is a tuple  $\mathcal{V} = (\Sigma, n, \delta)$  where  $\Sigma$  is a non-empty finite alphabet,  $n \in \mathbb{N}$  is the *dimension* and  $\delta \in \Sigma \rightarrow \mathbb{Z}^n$  is the *displacement function*. A *configuration* is a vector in  $\mathbb{N}^n$ . The binary relation  $\xrightarrow{a}_{\mathcal{V}}$  where  $a \in \Sigma$  over the set of configurations is defined by  $\mathbf{s} \xrightarrow{a}_{\mathcal{V}} \mathbf{s}'$  if and only if  $\mathbf{s}' = \mathbf{s} + \delta(a)$ . Given a word  $\sigma = a_1 \dots a_k$  of  $k \in \mathbb{N}$  elements  $a_i \in \Sigma$ , we denote by  $\xrightarrow{\sigma}_{\mathcal{V}}$  the binary relation over the set of configurations equals to the concatenation  $\xrightarrow{a_1}_{\mathcal{V}} \dots \xrightarrow{a_k}_{\mathcal{V}}$  if  $k \geq 1$  and equals to the identity binary relation if  $k = 0$ . We also denotes by  $\rightarrow_{\mathcal{V}}$  the *reachability binary relation* over the set of configurations defined by  $\mathbf{s} \rightarrow_{\mathcal{V}} \mathbf{s}'$  if and only if there exists  $\sigma \in \Sigma^*$  such that  $\mathbf{s} \xrightarrow{\sigma}_{\mathcal{V}} \mathbf{s}'$ . Given two sets  $S, S'$  of configurations, we denote by  $\text{post}_{\mathcal{V}}^*(S)$  and  $\text{pre}_{\mathcal{V}}^*(S')$  respectively the set of *reachable states from S* and the set of *co-reachable states from S'* formally defined by:

$$\begin{aligned} \text{post}_{\mathcal{V}}^*(S) &= \{\mathbf{s}' \in \mathbb{N}^n \mid \exists \mathbf{s} \in S \quad \mathbf{s} \rightarrow_{\mathcal{V}} \mathbf{s}'\} \\ \text{pre}_{\mathcal{V}}^*(S') &= \{\mathbf{s} \in \mathbb{N}^n \mid \exists \mathbf{s}' \in S' \quad \mathbf{s} \rightarrow_{\mathcal{V}} \mathbf{s}'\} \end{aligned}$$

The reachability problem for a tuple  $(\mathbf{s}, \mathcal{V}, \mathbf{s}')$  where  $\mathbf{s}, \mathbf{s}'$  are two configurations of a VAS  $\mathcal{V}$  consists to decide if  $\mathbf{s} \rightarrow_{\mathcal{V}} \mathbf{s}'$ . This problem can be reformulated by introducing the definition of separators. A pair  $(S, S')$  of configuration sets is said *separable* if  $\text{post}_{\mathcal{V}}^*(S) \cap \text{pre}_{\mathcal{V}}^*(S') = \emptyset$ . Naturally, a pair  $(\mathbf{s}, \mathbf{s}')$  is in the complement of the reachability relation  $\rightarrow_{\mathcal{V}}$

if and only if the pair  $(\{\mathbf{s}\}, \{\mathbf{s}'\})$  is separable. A *separator* for a pair  $(S, S')$  of configuration sets is a pair  $(I, I')$  such that  $I \cap I' = \emptyset$  and such that  $I$  is a *forward invariant*  $\text{post}_{\mathcal{V}}^*(I) = I$  containing  $S \subseteq I$  and  $I'$  is a *backward invariant*  $\text{pre}_{\mathcal{V}}^*(I') = I'$  containing  $S' \subseteq I'$ . Observe that in this case  $(S, S')$  is separable. As  $(\text{post}_{\mathcal{V}}^*(S), \text{pre}_{\mathcal{V}}^*(S'))$  is a separator for any separable pair  $(S, S')$ , we deduce that a pair  $(S, S')$  is separable if and only if there exists a separator  $(I, I')$  for  $(S, S')$ .

We are interested in separators definable in the decidable logic  $\text{FO}(\mathbb{N}, +, \leq)$ . Note that a pair  $(\psi(\mathbf{x}), \psi'(\mathbf{x}))$  of formulas in this logic denotes a separator  $(I, I')$  if and only if  $\psi(\mathbf{x}) \wedge \psi'(\mathbf{x})$  and the following formulas are unsatisfiable for any  $a \in \Sigma$ . In particular we can effectively decide if  $(\psi(\mathbf{x}), \psi'(\mathbf{x}))$  denotes a separator.

$$\begin{aligned} \psi(\mathbf{x}) \quad \wedge \quad \mathbf{x}' = \mathbf{x} + \delta(a) \quad \wedge \quad \neg \psi(\mathbf{x}') \\ \psi'(\mathbf{x}') \quad \wedge \quad \mathbf{x}' = \mathbf{x} + \delta(a) \quad \wedge \quad \neg \psi'(\mathbf{x}) \end{aligned}$$

In this paper we prove that there exists a separator  $(I, I')$  definable in  $\text{FO}(\mathbb{N}, +, \leq)$  for any pair  $(S, S')$  of separable sets definable in  $\text{FO}(\mathbb{N}, +, \leq)$ . We deduce that algorithm **Reachability**( $\mathbf{s}, \mathcal{V}, \mathbf{s}'$ ) decides the reachability problem. The termination is guaranty by the previous result. Note [5] that in general, the separator  $(\text{post}_{\mathcal{V}}^*(S), \text{pre}_{\mathcal{V}}^*(S'))$  is not definable in  $\text{FO}(\mathbb{N}, +, \leq)$  even if  $S$  and  $S'$  are reduced to single vectors  $S = \{\mathbf{s}\}$  and  $S' = \{\mathbf{s}'\}$ . That means, this separator must be over-approximated by another separator  $(I, I')$  definable in  $\text{FO}(\mathbb{N}, +, \leq)$ . Intuitively, the approximation is obtained by observing that  $\text{post}_{\mathcal{V}}^*(S) \cap S'$  and  $S \cap \text{pre}_{\mathcal{V}}^*(S')$  are *semi-pseudo-linear* for any pair  $(S, S')$  of sets definable in  $\text{FO}(\mathbb{N}, +, \leq)$ , a class of sets that can be precisely over-approximated by semi-linear sets.

## 3. SEMI-PSEUDO-LINEAR SETS

In this section we introduce the class of *pseudo-linear sets* and *semi-pseudo-linear sets*. We show that a pseudo-linear set  $X$  can be precisely over-approximated by a *linear set*  $L$  called a *linearization* of  $X$ . We also introduce a monotonic function  $\dim : (P(\mathbb{Z}^n), \subseteq) \rightarrow (\{-\infty, 0, \dots, n\}, \leq)$  that associates to any set  $X \subseteq \mathbb{Z}^n$  a *dimension*  $\dim(X)$ . We show that  $\dim(X_1 \cup X_2) = \max\{\dim(X_1), \dim(X_2)\}$  for any  $X_1, X_2 \subseteq \mathbb{Z}^n$ . Essentially, in this section, we prove that any linearizations  $L_1, L_2$  of pseudo-linear sets  $X_1, X_2$  with an empty intersection  $X_1 \cap X_2 = \emptyset$  satisfy  $\dim(L_1 \cap L_2) < \max\{\dim(X_1), \dim(X_2)\}$ .

We first associate a dimension to sets  $X \subseteq \mathbb{Z}^n$ . The *dimension*  $\dim(X)$  of a non-empty set  $X \subseteq \mathbb{Z}^n$  is the minimal integer  $d \in \{0, \dots, n\}$  such that:

$$\sup_{k \geq 0} \frac{|X \cap \{-k, \dots, k\}^n|}{(1 + 2k)^d} < +\infty$$

The dimension of the empty-set set is denoted by  $\dim(\emptyset) = -\infty$ . Let us observe some immediate properties satisfied by the dimension function. First of all, we have  $\dim(X) \leq 0$  if and only if  $X$  is finite. The dimension function is monotonic  $\dim(X_1) \leq \dim(X_2)$  for any  $X_1 \subseteq X_2$ . Moreover it satisfies  $\dim(X_1 \cup X_2) = \max\{\dim(X_1), \dim(X_2)\}$  and  $\dim(X_1 +$

$X_2) \leq \dim(X_1) + \dim(X_2)$ . In particular  $\dim(\mathbf{v} + X) = \dim(X)$  for any  $\mathbf{v} \in \mathbb{Z}^n$  and for any  $X \subseteq \mathbb{Z}^n$ .

Now, let us recall the definition of *semi-linear sets*. In the sequel, a finite set  $P \subseteq \mathbb{Z}^n$  is called a *set of periods*. The *monoid*  $P^*$  generated by a set of periods  $P = \{\mathbf{p}_1, \dots, \mathbf{p}_k\}$  is the set  $P^* = \mathbb{N}\mathbf{p}_1 + \dots + \mathbb{N}\mathbf{p}_k$  if  $k \geq 1$  and  $P^* = \{\mathbf{0}\}$  if  $k = 0$ . A set  $L \subseteq \mathbb{Z}^n$  is said *linear* if there exists a vector  $\mathbf{b} \in \mathbb{Z}^n$  and a set of periods  $P \subseteq \mathbb{Z}^n$  such that  $L = \mathbf{b} + P^*$ . A *semi-linear set*  $S \subseteq \mathbb{Z}^n$  is a finite union of linear sets  $L_i \subseteq \mathbb{Z}^n$ . Recall that sets definable in  $\text{FO}(\mathbb{Z}, \mathbb{N}, +, \leq)$  are exactly the semi-linear sets and sets definable in  $\text{FO}(\mathbb{N}, +, \leq)$  are exactly the non-negative semi-linear sets [3].

The definition of semi-pseudo-linear sets requires the definition of *groups* and *attractors*. The *group*  $G$  generated by a set of periods  $P = \{\mathbf{p}_1, \dots, \mathbf{p}_k\}$  is the set  $G = \mathbb{Z}\mathbf{p}_1 + \dots + \mathbb{Z}\mathbf{p}_k$  if  $k \geq 1$  and the set  $G = \{\mathbf{0}\}$  if  $k = 0$ . An *attractor* of the monoid  $P^*$  is a vector  $\mathbf{a} \in P^*$  such that for any  $\mathbf{g} \in G$  there exists  $N \in \mathbb{N}$  such that  $\mathbf{g} + N\mathbf{a} \in P^*$ . We denote by  $\mathcal{A}(P^*)$  the *set of attractors* of  $P^*$ . The following Lemma 1 characterizes the set  $\mathcal{A}(P^*)$ . In particular, this lemma shows that  $\mathcal{A}(P^*)$  is non empty.

LEMMA 1. *We have  $\mathcal{A}(P^*) = \{\mathbf{0}\}$  if  $k = 0$  and  $\mathcal{A}(P^*) = P^* \cap ((\mathbb{Q}_+ \setminus \{0\})\mathbf{p}_1 + \dots + (\mathbb{Q}_+ \setminus \{0\})\mathbf{p}_k)$  if  $k \geq 1$  for any set of periods  $P = \{\mathbf{p}_1, \dots, \mathbf{p}_k\}$ .*

PROOF. Since the case  $k = 0$  is immediate, we assume that  $k \geq 1$ . Let us first consider an attractor  $\mathbf{a} \in \mathcal{A}(P^*)$ . As  $\mathbf{a} - \sum_{j=1}^k \mathbf{p}_j \in G$  there exists  $N \in \mathbb{N}$  such that the vector  $\mathbf{p} = \mathbf{a} - \sum_{j=1}^k \mathbf{p}_j + N\mathbf{a}$  is in  $P^*$ . Hence, there exists a sequence  $(N_j)_{1 \leq j \leq k}$  in  $\mathbb{N}$  such that  $\mathbf{p} = \sum_{j=1}^k N_j \mathbf{p}_j$ . Combining this equality with the previous one provides  $\mathbf{a} = \sum_{j=1}^k \frac{1+N_j}{1+N} \mathbf{p}_j$ . Thus  $\mathbf{a} \in (\mathbb{Q}_+ \setminus \{0\})\mathbf{p}_1 + \dots + (\mathbb{Q}_+ \setminus \{0\})\mathbf{p}_k$ . Conversely, let us consider  $\mathbf{a} \in P^* \cap ((\mathbb{Q}_+ \setminus \{0\})\mathbf{p}_1 + \dots + (\mathbb{Q}_+ \setminus \{0\})\mathbf{p}_k)$ . Observe that there exists an integer  $d \geq 1$  larger enough such that  $d\mathbf{a} \in (\mathbb{N} \setminus \{0\})\mathbf{p}_1 + \dots + (\mathbb{N} \setminus \{0\})\mathbf{p}_k$ . In particular for any  $\mathbf{g} \in G$  there exists  $N \in \mathbb{N}$  such that  $\mathbf{g} + N d\mathbf{a} \in P^*$ .  $\square$

EXAMPLE 1. *Let  $P = \{(1, 1), (1, 0)\}$ . The monoid generated by  $P$  is equal to  $P^* = \{\mathbf{x} \in \mathbb{N}^2 \mid \mathbf{x}[2] \leq \mathbf{x}[1]\}$ , the group generated by  $P$  is equal to  $G = \mathbb{Z}^2$ , and the set of attractors of  $P^*$  is equal to  $\mathcal{A}(P^*) = \{\mathbf{x} \in \mathbb{N}^2 \mid 0 < \mathbf{x}[2] < \mathbf{x}[1]\}$ .*

A set  $X \subseteq \mathbb{Z}^n$  is said *pseudo-linear* if there exists  $\mathbf{b} \in \mathbb{Z}^n$  and a set of periods  $P \subseteq \mathbb{Z}^n$  such that  $X \subseteq \mathbf{b} + P^*$  and such that for any finite set  $R \subseteq \mathcal{A}(P^*)$  there exists  $\mathbf{x} \in X$  such that  $\mathbf{x} + R \subseteq X$ . In this case,  $P$  is called a *linearizator* of  $X$  and the linear set  $L = \mathbf{b} + P^*$  is called a *linearization* of  $X$ . A *semi-pseudo-linear set* is a finite union of *pseudo-linear sets*.

EXAMPLE 2. *The set  $P = \{(1, 1), (1, 0)\}$  is a linearizator of the pseudo-linear set  $X = \{\mathbf{x} \in \mathbb{N}^2 \mid \mathbf{x}[2] \leq \mathbf{x}[1] \leq 2^{\mathbf{x}[2]}\}$ . Moreover  $P^*$  is a linearization of  $X$ .*

All other results and notations introduced in this section are not used in the sequel. The reader may safely skip the remaining of this section to read the other ones. In sub-section 3.1 we characterize the dimension of linear sets and pseudo-linear sets. This characterization is used in the next sub-section 3.2 to prove that linearizations  $L_1, L_2$  of two pseudo-linear sets  $X_1, X_2$  with an empty intersection  $X_1 \cap X_2 = \emptyset$  satisfy the strict inequality  $\dim(L_1 \cap L_2) < \max\{\dim(X_1), \dim(X_2)\}$ .

In these sub-sections, *vector spaces* are used. A *vector space*  $V$  generated by a set of periods  $P = \{\mathbf{p}_1, \dots, \mathbf{p}_k\}$  is the set  $V = \mathbb{Q}\mathbf{p}_1 + \dots + \mathbb{Q}\mathbf{p}_k$  if  $k \geq 1$  and the set  $V = \{\mathbf{0}\}$  if  $k = 0$ . A *basis* of a vector space  $V \neq \{\mathbf{0}\}$  is a sequence  $\mathbf{v}_1, \dots, \mathbf{v}_d \in V$  with  $d \geq 1$  such that for any  $\mathbf{v} \in V$  there exists a unique sequence  $\lambda_1, \dots, \lambda_d \in \mathbb{Q}$  such that  $\mathbf{v} = \sum_{j=1}^d \lambda_j \mathbf{v}_j$ . When  $V = \{\mathbf{0}\}$  the empty sequence with  $d = 0$  is called the basis of  $V$ . Any vector space  $V$  has at least one basis  $\mathbf{v}_1, \dots, \mathbf{v}_d \in V$ . The integer  $d$  is unique and it is called the *rank* of  $V$ .

### 3.1 Dimension of (pseudo-)linear sets

In this section, we prove that the dimension of a pseudo-linear set  $X$  and the dimension of a linearization  $L$  of  $X$  are equal. Moreover, the dimension of a linear set  $L = \mathbf{b} + P^*$  is proved equal to  $\text{rank}(V)$  where  $V$  is the vector space generated by the set of periods  $P$ . These two results are proved in the following Lemmas 2 and 3.

LEMMA 2. *We have  $\dim(L) = \text{rank}(V)$  where  $L = \mathbf{b} + P^*$  is a linear set with a set of periods  $P$  that generates a vector space  $V$ .*

PROOF. Since  $P^* \subseteq \mathbb{Z}^n \cap V$  it is sufficient to prove that  $\dim(P^*) \geq \text{rank}(V)$  and  $\dim(\mathbb{Z}^n \cap V) \leq \text{rank}(V)$ . Let us denote by  $\|\mathbf{x}\|_\infty = \max\{|\mathbf{x}[1]|, \dots, |\mathbf{x}[k]|\}$  the usual  $\infty$ -norm of a vector  $\mathbf{x} \in \mathbb{Q}^n$ . As  $P$  generates the vector space  $V$  recall that there exists a basis  $\mathbf{p}_1, \dots, \mathbf{p}_d \in P$  of the vector space  $V$  with  $d = \text{rank}(V)$ . Since the case  $d = 0$  is immediate we assume that  $d \geq 1$ . We denote by  $f: \mathbb{Q}^d \rightarrow V$  the injective linear function satisfying  $f(\mathbf{x}) = \sum_{i=1}^d \mathbf{x}[i] \mathbf{p}_i$ .

Let us first prove that  $\dim(P^*) \geq d$ . As the function  $f$  is injective, the cardinal of  $f(\{0, \dots, k\}^d)$  is equal to  $(1 + k)^d$ . Note that a vector  $\mathbf{y}$  in this set satisfies  $\|\mathbf{y}\|_\infty \leq k \sum_{i=1}^d \|\mathbf{p}_i\|_\infty$  and  $\mathbf{y} \in P^*$ . We deduce that  $\dim(P^*) \geq d$ .

Now, let us prove that  $\dim(\mathbb{Z}^n \cap V) \leq d$ . Since for any matrix, the rank of the column vectors is equal to the rank of the line vectors, there exists a sequence  $1 \leq j_1 < \dots < j_d \leq n$  such that the linear function  $g: \mathbb{Q}^n \rightarrow \mathbb{Q}^d$  defined by  $g(\mathbf{x}) = (\mathbf{x}[j_1], \dots, \mathbf{x}[j_d])$  satisfies  $h = g \circ f$  is a bijective linear function. In particular we deduce that for any  $\mathbf{v} \in \mathbb{Z}^n \cap V \cap \{-k, \dots, k\}^n$  there exists a vector  $\mathbf{x} = g(\mathbf{v}) \in \{-k, \dots, k\}^d$  such that  $\mathbf{v} = f \circ h^{-1}(\mathbf{x})$ . Therefore  $|\mathbb{Z}^n \cap V \cap \{-k, \dots, k\}^n| \leq (1 + 2k)^d$  for any  $k \in \mathbb{N}$ . We deduce that  $\dim(\mathbb{Z}^n \cap V) \leq d$ .  $\square$

LEMMA 3. For any pseudo-linear set  $X \subseteq \mathbb{Z}^n$ , we have  $\dim(X) = \text{rank}(V)$  where  $V$  is the vector space generated by a linearizator  $P$  of  $X$ .

PROOF. Let  $P$  be a linearizator of a pseudo-linear set  $X$  and let  $V$  be the vector space generated by  $P$ . Note that there exists a vector  $\mathbf{b} \in \mathbb{Z}^n$  such that  $X \subseteq \mathbf{b} + P^*$ . From Lemma 2 we have  $\dim(\mathbf{b} + P^*) = \text{rank}(V)$ . In particular  $\dim(X) \leq \text{rank}(V)$ . Conversely, let us consider an attractor  $\mathbf{a} \in \mathcal{A}(P^*)$  and observe that  $R = \{\mathbf{a}\} + (\mathbf{a} + P) \subseteq \mathcal{A}(P^*)$ . As  $X$  is pseudo-linear, there exists  $\mathbf{x} \in X$  such that  $\mathbf{x} + R^* \subseteq X$ . Note that the vector space generated by  $R$  is equal to  $V$ . Thus, from Lemma 2 we deduce that  $\dim(\mathbf{x} + R^*) = \text{rank}(V)$ . In particular  $\dim(X) \geq \text{rank}(V)$ . We have proved the equality  $\dim(X) = \text{rank}(V)$ .  $\square$

### 3.2 Pseudo-linear sets intersection

In this section we prove that linearizations  $L_1, L_2$  of two pseudo-linear sets  $X_1, X_2$  with an empty intersection  $X_1 \cap X_2 = \emptyset$  satisfy  $\dim(L_1 \cap L_2) < \max\{\dim(X_1), \dim(X_2)\}$ .

We first characterize the intersection of two linear sets.

LEMMA 4. For any set of periods  $P_1, P_2$  there exists a set of periods  $P$  such that  $P_1^* \cap P_2^* = P^*$ . Moreover, for any  $\mathbf{b}_1, \mathbf{b}_2 \in \mathbb{Z}^n$ , there exists a finite set  $B \subseteq \mathbb{Z}^n$  such that  $(\mathbf{b}_1 + P_1^*) \cap (\mathbf{b}_2 + P_2^*) = B + (P_1^* \cap P_2^*)$ .

PROOF. Let us consider an enumeration  $\mathbf{p}_{i,1}, \dots, \mathbf{p}_{i,k_i}$  of the  $k_i \geq 0$  vectors in  $P_i$  where  $i \in \{1, 2\}$ . If  $k_1 = 0$  or if  $k_2 = 0$  then  $P_1^* = \{\mathbf{0}\}$  or  $P_2^* = \{\mathbf{0}\}$  and the lemma is immediate. Thus, we can assume that  $k_1, k_2 \geq 1$ .

Let us consider the set  $X$  of vectors  $(\lambda_1, \lambda_2) \in \mathbb{N}^{k_1} \times \mathbb{N}^{k_2}$  such that  $\mathbf{b}_1 + \sum_{j=1}^{k_1} \lambda_1[j] \mathbf{p}_{1,j} = \mathbf{b}_2 + \sum_{j=1}^{k_2} \lambda_2[j] \mathbf{p}_{2,j}$ . Let us also consider the set  $X_0$  of vectors  $(\lambda_1, \lambda_2) \in \mathbb{N}^{k_1} \times \mathbb{N}^{k_2}$  such that  $\sum_{j=1}^{k_1} \lambda_1[j] \mathbf{p}_{1,j} = \sum_{j=1}^{k_2} \lambda_2[j] \mathbf{p}_{2,j}$ . Observe that  $X = Z + X_0$  where  $Z$  is the finite set  $Z = \min(X)$  and  $X_0 = Z_0^*$  where  $Z_0$  is the finite set  $Z_0 = \min(X_0 \setminus \{\mathbf{0}\})$ .

Let us denote by  $B$  the finite set of vectors  $\mathbf{b} \in \mathbb{Z}^n$  such that there exists  $(\lambda_1, \lambda_2) \in Z$  satisfying  $\mathbf{b}_1 + \sum_{j=1}^{k_1} \lambda_1[j] \mathbf{p}_{1,j} = \mathbf{b} = \mathbf{b}_2 + \sum_{j=1}^{k_2} \lambda_2[j] \mathbf{p}_{2,j}$ . Let us also denote by  $P$  the finite set of vectors  $\mathbf{p} \in \mathbb{Z}^n$  such that there exists  $(\lambda_1, \lambda_2) \in Z_0$  satisfying  $\sum_{j=1}^{k_1} \lambda_1[j] \mathbf{p}_{1,j} = \mathbf{p} = \sum_{j=1}^{k_2} \lambda_2[j] \mathbf{p}_{2,j}$ . Remark that  $(\mathbf{b}_1 + P_1^*) \cap (\mathbf{b}_2 + P_2^*) = B + P^*$  and  $P_1^* \cap P_2^* = P^*$ .  $\square$

We now prove the main result of this section.

PROPOSITION 1. Let  $L_1, L_2$  be linearizations of pseudo-linear sets  $X_1, X_2 \subseteq \mathbb{Z}^n$  with an empty intersection  $X_1 \cap X_2 = \emptyset$ . We have:

$$\dim(L_1 \cap L_2) < \max\{\dim(X_1), \dim(X_2)\}$$

PROOF. Let  $L_1, L_2$  be linearizations of two pseudo-linear sets  $X_1, X_2 \subseteq \mathbb{Z}^n$ . For the moment, we do not assume that

$X_1 \cap X_2$  is empty. There exists some linearizators  $P_1, P_2$  of the pseudo-linear sets  $X_1, X_2$  and vectors  $\mathbf{b}_1, \mathbf{b}_2 \in \mathbb{Z}^n$  such that  $L_1 = \mathbf{b}_1 + P_1^*$  and  $L_2 = \mathbf{b}_2 + P_2^*$  are linearizations of  $X_1, X_2$ . Let us denote by  $V_1, V_2$  the vector spaces generated by  $P_1, P_2$ . Lemma 3 shows that  $\dim(X_1) = \text{rank}(V_1)$  and  $\dim(X_2) = \text{rank}(V_2)$ . From Lemma 4 there exists a set of periods  $P$  and a finite set  $B \subseteq \mathbb{Z}^n$  such that  $P_1^* \cap P_2^* = P^*$  and  $L_1 \cap L_2 = B + P^*$ . Observe that if  $B = \emptyset$  then  $X_1 \cap X_2 = \emptyset$  and the proposition is proved. Thus, we can assume that there exists  $\mathbf{b} \in B$ . Let  $V$  be the vector space generated by  $P$ . Lemma 2 shows that  $\dim(B + P^*) = \text{rank}(V)$ . Observe that  $V \subseteq V_1 \cap V_2$ . Thus, if there exists  $j \in \{1, 2\}$  such that  $V$  is strictly included in  $V_j$  then  $\text{rank}(V) < \text{rank}(V_j)$  and in this case  $\dim(L_1 \cap L_2) < \max\{\dim(X_1), \dim(X_2)\}$ . Let us assume that  $V_1 = V = V_2$  and let us prove that  $X_1 \cap X_2 \neq \emptyset$ .

We denote by  $G_1, G, G_2$  the groups generated respectively by  $P_1, P, P_2$ .

Let  $\mathbf{a}$  be an attractor of  $P^*$  and let us prove that  $\mathbf{a} \in \mathcal{A}(P_j^*)$ . Note that  $\mathbf{a} \in P^* \subseteq P_j^*$ . Let  $\mathbf{p} \in \mathcal{A}(P_j^*)$ . Since  $-\mathbf{p} \in V$  and  $V$  is the vector space generated by  $P$ , there exists an integer  $d \geq 1$  such that  $-d\mathbf{p} \in G$ . From  $\mathbf{a} - d\mathbf{p} \in G$  and  $\mathbf{a} \in \mathcal{A}(P^*)$  we deduce that there exists  $N \in \mathbb{N}$  such that  $\mathbf{a} - d\mathbf{p} + N\mathbf{a} \in P^*$ . From  $P^* \subseteq P_j^*$  we deduce that  $\mathbf{a} \in \frac{1}{1+N}(d\mathbf{p} + P_j^*)$ . From  $\mathbf{p} \in \mathcal{A}(P_j^*)$  and Lemma 1 we get  $\mathbf{a} \in \mathcal{A}(P_j^*)$ .

Let  $R_j = \{\mathbf{a}\} \cup (\mathbf{a} + P_j)$ . From  $\mathbf{a} \in \mathcal{A}(P_j^*)$ , Lemma 1 shows that  $R_j \subseteq \mathcal{A}(P_j^*)$ . As  $X_j$  is pseudo-linear, there exists  $\mathbf{x}_j \in X_j$  such that  $\mathbf{x}_j + R_j^* \subseteq X_j$ . From  $\mathbf{b}, \mathbf{x}_j \in \mathbf{b}_j + P_j^*$  we deduce that  $\mathbf{x}_j - \mathbf{b} \in G_j$ . As the group generated by  $R_j$  is equal to  $G_j$ , there exists  $\mathbf{r}_j, \mathbf{r}'_j \in R_j^*$  such that  $\mathbf{x}_j + \mathbf{r}_j = \mathbf{b} + \mathbf{r}'_j$ .

As  $V$  is the vector space generated by  $P_1$  and  $\mathbf{r}'_2 \in R_2^* \subseteq V$  there exists an integer  $d_1 \geq 1$  such that  $d_1 \mathbf{r}'_2 \in G_1$ . As  $\mathbf{a} \in \mathcal{A}(P_1^*)$ , there exists an integer  $N_1 \geq 0$  such that  $d_1 \mathbf{r}'_2 + N_1 \mathbf{a} \in P_1^*$ . As  $P_1^* \subseteq R_1^* - N\mathbf{a}$ , we deduce that there exists an integer  $N'_1 \geq 0$  such that  $d_1 \mathbf{r}'_2 + (N_1 + N'_1) \mathbf{a} \in R_1^*$ . We denote by  $\mathbf{r}''_1$  this vector. Symmetrically, there exist some integers  $d_2 \geq 1$  and  $N_2, N'_2 \geq 0$  such that the vector  $d_2 \mathbf{r}'_1 + (N_2 + N'_2) \mathbf{a}$  denoted by  $\mathbf{r}''_2$  is in  $R_2^*$ . We get:

$$\begin{aligned} \mathbf{x}_1 + \mathbf{r}_1 + (d_2 - 1) \mathbf{r}'_1 + \mathbf{r}''_1 + (N_2 + N'_2) \mathbf{a} \\ = \mathbf{b} + d_2 \mathbf{r}'_1 + d_1 \mathbf{r}'_2 + (N_1 + N'_1 + N_2 + N'_2) \mathbf{a} \\ = \mathbf{b} + d_1 \mathbf{r}'_2 + d_2 \mathbf{r}'_1 + (N_2 + N'_2 + N_1 + N'_1) \mathbf{a} \\ \mathbf{x}_2 + \mathbf{r}_2 + (d_1 - 1) \mathbf{r}'_2 + \mathbf{r}''_2 + (N_1 + N'_1) \mathbf{a} \end{aligned}$$

We have proved that this last vector is in  $(\mathbf{x}_1 + R_1^*) \cap (\mathbf{x}_2 + R_2^*)$ . In particular  $X_1 \cap X_2 \neq \emptyset$ .  $\square$

## 4. REACHABILITY SETS

In this section we prove that  $\text{post}_V^*(S) \cap S'$  and  $S \cap \text{pre}_V^*(S')$  are semi-pseudo-linear for any semi-linear sets  $S, S' \subseteq \mathbb{N}^n$ . All other results and notations introduced in this section are not used in the sequel. The reader may safely skip the remaining of this section in order to read the other ones. In sub-section 4.1 we recall the classical Kosaraju-Lambert-Mayr-Sacerdote-Tenney (KLMST) decomposition. This decomposition is used in the next sub-section 4.2 to establish the semi-pseudo-linearity of the reachability sets.

## 4.1 Languages Accepted

The *language accepted*  $\mathcal{L}(\mathbf{b}, \mathcal{V}, \mathbf{b}')$  by a tuple  $(\mathbf{b}, \mathcal{V}, \mathbf{b}')$  where  $(\mathbf{b}, \mathbf{b}')$  are two configurations of a VAS  $\mathcal{V}$  is the set of words  $\sigma \in \Sigma^*$  such that  $\mathbf{b} \xrightarrow{\sigma}_{\mathcal{V}} \mathbf{b}'$ . In this section we recall the KLMST decomposition by following notations introduced by Lambert [8].

We first extend the set of non-negative integers  $\mathbb{N}$  with an additional element  $\top$ . In the sequel, this element is either interpreted as a “very large integer” or a “don’t care integer”. More formally, we denote by  $\mathbb{N}_{\top}$  the set  $\mathbb{N} \cup \{\top\}$ . The total order  $\leq$  over  $\mathbb{N}$  is extended over  $\mathbb{N}_{\top}$  by  $x_1 \leq x_2$  if and only if  $x_2 = \top \vee (x_1, x_2 \in \mathbb{N} \wedge x_1 \leq x_2)$ . The equality  $=$  over  $\mathbb{N}$  is also extended to a partial order  $\leq$  over  $\mathbb{N}_{\top}$  by  $x_1 \leq x_2$  if and only if  $x_2 = \top \vee (x_1, x_2 \in \mathbb{N} \wedge x_1 = x_2)$ . Intuitively the elements  $\top$  denotes a “very large integer” for the total order  $\leq$  whereas it denotes a “don’t care integer” for the partial order  $\leq$ . Given a sequence  $(x_i)_{i \geq 0}$  in  $\mathbb{N}_{\top}$ , we denote by  $x = \lim_{i \rightarrow +\infty} x_i$  the element  $x = \top$  if for any  $r \in \mathbb{N}$  there exists  $i_0 \geq 0$  such that  $x_i \geq r$  for any  $i \geq i_0$  and the element  $x \in \mathbb{N}$  if there exists  $i_0 \geq 0$  such that  $x_i = x$  for any  $i \geq i_0$ . When  $x = \lim_{i \rightarrow +\infty} x_i$  exists we say that  $(x_i)_{i \geq 0}$  *converges towards*  $x$ .

We also extends the semantics of VAS. A vector in  $\mathbb{N}_{\top}^2$  is called an *extended configuration* of  $\mathcal{V}$ . The addition function  $+: \mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Z}$  is extended to the totally-defined function in  $(\mathbb{Z} \cup \{\top\}) \times (\mathbb{Z} \cup \{\top\}) \rightarrow (\mathbb{Z} \cup \{\top\})$  satisfying  $x_1 + x_2 = \top$  if  $x_1 = \top$  or  $x_2 = \top$ . With slightly abusing notations, the binary relation  $\xrightarrow{a}_{\mathcal{V}}$  where  $a \in \Sigma$  over the set of extended configurations is defined by  $\mathbf{x} \xrightarrow{a}_{\mathcal{V}} \mathbf{x}'$  if and only if  $\mathbf{x}' = \mathbf{x} + \delta(a)$ . Given a word  $\sigma = a_1 \dots a_k$  of  $k \in \mathbb{N}$  elements  $a_i \in \Sigma$ , we denote by  $\xrightarrow{\sigma}_{\mathcal{V}}$  the binary relation over the set of extended configurations equals to the concatenation  $\xrightarrow{a_1}_{\mathcal{V}} \dots \xrightarrow{a_k}_{\mathcal{V}}$  if  $k \geq 1$  and equals to the identity binary relation if  $k = 0$ . Given an extended configuration  $\mathbf{x}$  we denote by  $\mathbf{x} \xrightarrow{\sigma}_{\mathcal{V}}$  if there exists an extended configuration  $\mathbf{x}'$  such that  $\mathbf{x} \xrightarrow{\sigma}_{\mathcal{V}} \mathbf{x}'$  and symmetrically for any extended configuration  $\mathbf{x}'$  we denote by  $\mathbf{x} \xrightarrow{\sigma}_{\mathcal{V}} \mathbf{x}'$  if there exists an extended configuration  $\mathbf{x}$  such that  $\mathbf{x} \xrightarrow{\sigma}_{\mathcal{V}} \mathbf{x}'$ .

Next we recall some elements of graph theory. An *alphabet*  $\Sigma$  is a non-empty finite set. We denote by  $\Sigma^*$  the set of finite words over  $\Sigma$ . A *graph*  $G$  is a tuple  $G = (Q, \Sigma, T)$  where  $Q$  is a finite set of *states*,  $\Sigma$  is a finite set of *labels*, and  $T \subseteq Q \times \Sigma \times Q$  is a finite set of *transitions*. A *path*  $\pi$  is a word  $\pi = t_1 \dots t_k$  of  $k \in \mathbb{N}$  transitions  $t_i \in T$  such that there exists  $q_0, \dots, q_k \in Q$  and  $a_1, \dots, a_k \in \Sigma$  such that  $t_i = (q_{i-1}, a_i, q_i)$  for any  $1 \leq i \leq k$ . In this case we say that  $\pi$  is a path from  $q_0$  to  $q_k$  labelled by  $\sigma = a_1 \dots a_k$  and we denote  $\pi$  by  $q_0 \xrightarrow{\sigma}_G q_k$  or simply  $q_0 \rightarrow_G q_k$ . When  $q_0 = q_k$ , the path  $\pi$  is called a *cycle*. Given a transition  $t \in T$ , we denote by  $|\pi|_t$  the number of occurrences of  $t$  in  $\pi$ . Let us recall the following lemma.

LEMMA 5 (EULER CYCLE). *Let  $G = (Q, \Sigma, T)$  be a strongly connected graph and let  $(\mu_t)_{t \in T}$  be a sequence in  $\mathbb{N} \setminus \{0\}$ . There exists a cycle  $\pi$  in  $G$  such that  $|\pi|_t = \mu_t$  for any transition  $t \in T$  if and only if for any state  $q_0 \in Q$  we have*

*the following equality:*

$$\sum_{t=(q,a,q_0) \in T} \mu_t = \sum_{t'=(q_0,a,q') \in T} \mu_{t'}$$

A *graph vector*  $G = (Q, \Sigma, T)$  for  $\mathcal{V}$  is a graph such that  $Q \subseteq \mathbb{N}_{\top}^2$  is a finite set of extended configurations, and  $T \subseteq Q \times \Sigma \times Q$  is a finite set of transitions  $(\mathbf{x}, a, \mathbf{x}')$  such that  $\mathbf{x} \xrightarrow{a}_{\mathcal{V}} \mathbf{x}'$ . Even if the proof of the following lemma is immediate by induction over the length of  $\sigma$ , it is central in the KLMST decomposition.

LEMMA 6 (GRAPH VECTOR PATHS). *Let us consider a path  $\mathbf{x} \xrightarrow{\sigma}_G \mathbf{x}'$  in a graph vector  $G$  for  $\mathcal{V}$ . For any sequences  $(\mathbf{x}_c)_{c \in \mathbb{N}}$  and  $(\mathbf{x}'_c)_{c \in \mathbb{N}}$  of extended configurations that converge toward  $\mathbf{x} = \lim_{c \rightarrow +\infty} \mathbf{x}_c$  and  $\mathbf{x}' = \lim_{c \rightarrow +\infty} \mathbf{x}'_c$ , there exists  $c_0 \in \mathbb{N}$  such that  $\mathbf{x}_c \xrightarrow{\sigma}_{\mathcal{V}}$  and  $\xrightarrow{\sigma}_{\mathcal{V}} \mathbf{x}'_c$  for any  $c \geq c_0$ .*

A *marked graph vector* is a tuple  $(\mathbf{m}, G, \mathbf{x}, \mathbf{m}')$  where  $G$  is a strongly connected graph vector,  $\mathbf{x}$  is a state of this graph vector and  $\mathbf{m}, \mathbf{m}' \leq \mathbf{x}$  are two extended configurations. A *marked graph vector sequences (MGVS)* for  $(\mathbf{b}, \mathcal{V}, \mathbf{b}')$  is an alternating sequence of marked graph vectors and actions of the following form where  $\mathbf{b} = \mathbf{m}_0$  and  $\mathbf{m}'_k = \mathbf{b}'$ :

$$\mathcal{U} = (\mathbf{m}_0, G_0, \mathbf{x}_0, \mathbf{m}_0'), a_1, \dots, a_k, (\mathbf{m}_k, G_k, \mathbf{x}_k, \mathbf{m}'_k)$$

The *language accepted* by a MGVS  $\mathcal{U}$  is the set  $\mathcal{L}(\mathcal{U})$  of words of the form  $\sigma_0 a_1 \dots a_k \sigma_k$  such that for any  $0 \leq j \leq k$  there exists a cycle  $\mathbf{x}_j \xrightarrow{\sigma_j}_{G_j} \mathbf{x}_j$  and there exists two configurations  $\mathbf{s}_j \leq \mathbf{m}_j$  and  $\mathbf{s}'_j \leq \mathbf{m}'_j$  such that:

$$\mathbf{s}_0 \xrightarrow{\sigma_0}_{\mathcal{V}} \mathbf{s}'_0 \xrightarrow{a_1}_{\mathcal{V}} \mathbf{s}_1 \dots \mathbf{s}'_{k-1} \xrightarrow{a_k}_{\mathcal{V}} \mathbf{s}_k \xrightarrow{\sigma_k}_{\mathcal{V}} \mathbf{s}'_k$$

We observe that  $\mathcal{L}(\mathcal{U}) \subseteq \mathcal{L}(\mathbf{b}, \mathcal{V}, \mathbf{b}')$  since  $(\mathbf{s}_0, \mathbf{s}'_k) = (\mathbf{b}, \mathbf{b}')$ .

We now associate a characteristic linear system to a MGVS  $\mathcal{U}$ . Denoting by  $\mu_{j,t}$  the number of occurrences of a transition  $t \in T_j$  in the cycle  $\mathbf{x}_j \xrightarrow{\sigma_j}_{G_j} \mathbf{x}_j$  we get a non-negative sequence  $(\mu_{j,t})_{j,t}$  indexed by  $0 \leq j \leq k$  and  $t \in T_j$ . We also obtain a tuple  $\xi = ((\mathbf{s}_j)_j, (\mu_{j,t})_{j,t}, (\mathbf{s}'_j)_j)$  said *associated* to  $\sigma$ . We observe that  $\xi$  is a non-negative solution of the following linear system called the *characteristic system* of the MGVS  $\mathcal{U}$ :

$$\left\{ \begin{array}{l} \text{for all } 1 \leq j \leq k \\ \mathbf{s}'_{j-1} + \delta(a_j) = \mathbf{s}_j \\ \\ \text{for all } 0 \leq j \leq k \\ \mathbf{s}_j + \sum_{t=(q,a,q') \in T_j} \mu_{j,t} \delta(a) = \mathbf{s}'_j \\ \\ \text{for all } 0 \leq j \leq k \text{ and for all } 1 \leq i \leq n \\ \mathbf{s}_j[i] = \mathbf{m}_j[i] \text{ if } \mathbf{m}_j[i] \in \mathbb{N} \\ \mathbf{s}'_j[i] = \mathbf{m}'_j[i] \text{ if } \mathbf{m}'_j[i] \in \mathbb{N} \\ \\ \text{for all } 0 \leq j \leq k \text{ and for all } q_j \in Q_j \\ \sum_{t=(q,a,q_j) \in T} \mu_{j,t} = \sum_{t'=(q_j,a,q') \in T} \mu_{j,t'} \end{array} \right.$$

Naturally there exists non-negative solutions  $\xi$  of the characteristic system that are not associated to an accepted word. In particular even if there exists non-negative solutions of the characteristic linear system we cannot conclude that  $\mathcal{L}(\mathcal{U}) \neq \emptyset$ . However, under the following *perfect* condition, we can prove that  $\mathcal{L}(\mathcal{U}) \neq \emptyset$ .

A MGVS  $\mathcal{U}$  is said *perfect* if for any integer  $c \geq 0$ , there exists a non-negative solution  $((\mathbf{s}_j)_j, (\mu_{j,t})_{j,t}, (\mathbf{s}'_j)_j)$  of the characteristic system of  $\mathcal{U}$  such that for any  $0 \leq j \leq k$  and for any  $1 \leq i \leq n$ :

- $\mathbf{s}_j[i] \geq c$  if  $\mathbf{m}_j[i] = \top$ , and
- $\mathbf{s}'_j[i] \geq c$  if  $\mathbf{m}'_j[i] = \top$ , and
- $\mu_{j,t} \geq c$  for any  $t \in T_j$ .

and such that for any  $0 \leq j \leq k$ :

- there exists a cycle  $\theta_j = (\mathbf{x}_j \xrightarrow{w_j}_{G_j} \mathbf{x}_j)$  such that  $\mathbf{m}_j \xrightarrow{w_j}_{\mathcal{V}}$  and such that  $\mathbf{m}_j + \delta(w_j) \geq \mathbf{m}_j$  and  $\delta(w_j)[i] > 0$  if  $\mathbf{m}_j[i] \in \mathbb{N}$  and  $\mathbf{x}_j[i] = \top$ .
- there exists a cycle  $\theta'_j = (\mathbf{x}_j \xrightarrow{w'_j}_{G_j} \mathbf{x}_j)$  such that  $\mathbf{m}'_j \xrightarrow{w'_j}_{\mathcal{V}}$  and such that  $\mathbf{m}'_j - \delta(w'_j) \geq \mathbf{m}'_j$  and  $-\delta(w'_j)[i] > 0$  if  $\mathbf{m}'_j[i] \in \mathbb{N}$  and  $\mathbf{x}_j[i] = \top$ .

Let us recall without proof the fundamental decomposition theorem.

**THEROEM 1** (FUNDAMENTAL DECOMPOSITION[8]). *For any tuple  $(\mathbf{b}, \mathcal{V}, \mathbf{b}')$ , we can effectively compute a finite sequence of perfect MGVS  $\mathcal{U}_1, \dots, \mathcal{U}_l$  for this tuple such that:*

$$\mathcal{L}(\mathbf{b}, \mathcal{V}, \mathbf{b}') = \mathcal{L}(\mathcal{U}_1) \cup \dots \cup \mathcal{L}(\mathcal{U}_l)$$

Let us now recall why  $\mathcal{L}(\mathcal{U}) \neq \emptyset$  for any perfect MGVS  $\mathcal{U}$ .

The homogeneous form of the characteristic system, obtained by replacing constants by zero, is called the *homogeneous characteristic system* of  $\mathcal{U}$ . A solution of the homogeneous form is denoted by  $\xi_0 = ((\mathbf{s}_{0,j})_j, (\mu_{0,j,t})_{j,t}, (\mathbf{s}'_{0,j})_j)$  in the sequel.

**LEMMA 7.** *There exists a solution of the homogeneous characteristic system  $\xi_0 = ((\mathbf{s}_{0,j})_j, (\mu_{0,j,t})_{j,t}, (\mathbf{s}'_{0,j})_j)$  and cycles  $\pi_{0,j} = (\mathbf{x}_j \xrightarrow{\sigma_{0,j}}_{G_j} \mathbf{x}_j)$  for any  $0 \leq j \leq k$  such that:*

- $\mu_{0,j,t} = |\theta_j|_t + |\pi_{0,j}|_t + |\theta'_j|_t$  for any  $t \in T_j$ ,
- $\mathbf{s}_{0,j} \geq \mathbf{0}$  and  $\mathbf{s}_{0,j}[i] > 0$  if and only if  $\mathbf{m}_j[i] = \top$ ,
- $\mathbf{s}_{0,j}' \geq \mathbf{0}$  and  $\mathbf{s}_{0,j}'[i] > 0$  if and only if  $\mathbf{m}'_j[i] = \top$ .
- $\mathbf{s}_{0,j} + \delta(w_j) \geq \mathbf{0}$  and  $(\mathbf{s}_{0,j} + \delta(w_j))[i] > 0$  if and only if  $\mathbf{x}_j[i] = \top$ ,

- $\mathbf{s}'_{0,j} - \delta(w'_j) \geq \mathbf{0}$  and  $(\mathbf{s}'_{0,j} - \delta(w'_j))[i] > 0$  if and only if  $\mathbf{x}_j[i] = \top$ ,

**PROOF.** As  $\mathcal{U}$  is perfect, for any integer  $c \geq 0$ , there exists a solution  $\xi(c) = ((\mathbf{s}_j(c))_j, (\mu_{j,t}(c))_{j,t}, (\mathbf{s}'_j(c))_j)$  of the characteristic system of  $\mathcal{U}$  such that for any  $0 \leq j \leq k$ :

- $\mathbf{s}_j(c)[i] \geq c$  if  $\mathbf{m}_j[i] = \top$ , and
- $\mathbf{s}'_j(c)[i] \geq c$  if  $\mathbf{m}'_j[i] = \top$ , and
- $\mu_{j,t}(c) \geq c$  for any  $t \in T_j$ .

Observe that  $\xi_0(c) = ((\mathbf{s}_{0,j}(c))_j, (\mu_{0,j,t}(c))_{j,t}, (\mathbf{s}'_{0,j}(c))_j)$  defined by  $\xi_0(c) = \xi(c) - \xi(0)$  is solution of the homogeneous characteristic system. Observe that there exists an integer  $c_0 \geq 0$  larger enough such that  $\mathbf{s}_{0,j}(c)[i] > 0$  if  $\mathbf{m}_j[i] = \top$ , such that  $\mathbf{s}'_{0,j}(c)[i] > 0$  if  $\mathbf{m}'_j[i] = \top$ , and such that  $|\mu_{0,j,t}(c)| > |\theta_j|_t + |\theta'_j|_t$  for any  $t \in T_j$  and for any integer  $c \geq c_0$ .

Let us prove that we can also assume the following properties for any  $c \geq c_0$ :

- $\mathbf{s}_{0,j}(c) + \delta(w_j) \geq \mathbf{0}$  and  $(\mathbf{s}_{0,j}(c) + \delta(w_j))[i] > 0$  if  $\mathbf{x}_j[i] = \top$ .
- $\mathbf{s}'_{0,j}(c) - \delta(w'_j) \geq \mathbf{0}$  and  $(\mathbf{s}'_{0,j}(c) - \delta(w'_j))[i] > 0$  if  $\mathbf{x}_j[i] = \top$ .

The two conditions are symmetrical. Let us just show the first one. Assume that  $\mathbf{x}_j[i] = \top$ . Consider the case  $\mathbf{m}_j[i] \in \mathbb{N}$ . The homogeneous characteristic system shows  $\mathbf{s}_{0,j}(c)[i] = 0$ . Moreover, by definition of  $\theta_j$ , as  $\mathbf{m}_j[i] < \mathbf{x}_j[i]$  we get  $\delta(w_j)[i] > 0$ . Thus  $(\mathbf{s}_{0,j}(c) + \delta(w_j))[i] > 0$  in this case. Now, assume that  $\mathbf{m}_j[i] = \top$ . In this case  $\mathbf{s}_{0,j}(c)[i] \geq c - \mathbf{s}_{0,j}(0)[i]$ . Thus by replacing  $c_0$  by a larger integer, we can assume that  $(\mathbf{s}_{0,j}(c) + \delta(w_j))[i] > 0$  for any  $c \geq c_0$ .

Let us consider  $\xi_0 = ((\mathbf{s}_{0,j})_j, (\mu_{0,j,t})_{j,t}, (\mathbf{s}'_{0,j})_j)$  defined by fixing  $c = c_0$  and formally given by  $\xi_0 = \xi_0(c_0)$ . Observe that if  $\mathbf{m}_j[i] \in \mathbb{N}$  then  $\mathbf{s}_{0,j}[i] = 0$ . Thus  $\mathbf{s}_{0,j} \geq \mathbf{0}$  and  $\mathbf{s}_{0,j}[i] > 0$  if and only if  $\mathbf{m}_j[i] = \top$ . Symmetrically we deduce that  $\mathbf{s}_{0,j}' \geq \mathbf{0}$  and  $\mathbf{s}_{0,j}'[i] > 0$  if and only if  $\mathbf{m}'_j[i] = \top$ . Observe also that if  $\mathbf{x}_j[i] \in \mathbb{N}$  then  $\mathbf{s}_{0,j}[i] = 0$  and  $\delta(w_j)[i] = 0$ . In particular  $(\mathbf{s}_{0,j} + \delta(w_j))[i] = 0$ . We deduce that  $\mathbf{s}_{0,j} + \delta(w_j) \geq \mathbf{0}$  and we have  $(\mathbf{s}_{0,j} + \delta(w_j))[i] > 0$  if and only if  $\mathbf{x}_j[i] = \top$ . Symmetrically  $\mathbf{s}'_{0,j} - \delta(w'_j) \geq \mathbf{0}$  and we have  $(\mathbf{s}'_{0,j} - \delta(w'_j))[i] > 0$  if and only if  $\mathbf{x}_j[i] = \top$ .

Finally, Lemma 5 provides a cycle  $\pi_{0,j} = (\mathbf{x}_j \xrightarrow{\sigma_{0,j}}_{G_j} \mathbf{x}_j)$  such that  $|\pi_{0,j}|_t = |\mu_{0,j,t}| - (|\theta_j|_t + |\theta'_j|_t)$  for any  $t \in T_j$ .  $\square$

As the MGVS  $\mathcal{U}$  is perfect, Lemma 6 shows that there exists a non-negative solution  $\xi = ((\mathbf{s}_j)_j, (\mu_{j,t})_{j,t}, (\mathbf{s}'_j)_j)$  of the characteristic system such that  $\mu_{j,t} \geq 1$  for any  $0 \leq j \leq k$  and  $t \in T_j$  and such that  $\mathbf{s}_j \xrightarrow{w_j}_{\mathcal{V}}$  and  $\mathbf{s}'_j \xrightarrow{\sigma_{0,j} w'_j}_{\mathcal{V}}$  for any

$0 \leq j \leq k$ . Let  $0 \leq j \leq k$ . From Lemma 5, there exists a cycle  $\pi_j = (\mathbf{x}_j \xrightarrow{\sigma_j}_{G_j} \mathbf{x}_j)$  such that  $\mu_{j,t} = |\pi_j|_t$  for any  $t \in T_j$ . Let us observe that for any  $c \in \mathbb{N}$  and for any  $0 \leq j \leq k$  we have:

$$(\mathbf{s}_j + c\mathbf{s}_{0,j}) \xrightarrow{w_j^c} \mathbf{s}_j' + c\mathbf{s}_{0,j}'$$

The first relation is obtained by observing that  $\mathbf{s}_{0,j} \geq \mathbf{0}$ ,  $\mathbf{s}_{0,j} + \delta(w_j) \geq \mathbf{0}$  and  $\mathbf{s}_j \xrightarrow{w_j} \mathbf{s}_j'$  whereas the second relation is obtained from  $\mathbf{s}_{0,j}' \geq \mathbf{0}$ ,  $\mathbf{s}_{0,j}' - \delta(w_j') \geq \mathbf{0}$ ,  $\mathbf{s}_{0,j}' - \delta(w_j') - \delta(\sigma_{0,j}) \geq \mathbf{0}$  (since this last vector is equal to  $\mathbf{s}_{0,j} \geq \mathbf{0}$ ) and  $\frac{\sigma_{0,j} w_j'}{w_j} \xrightarrow{w_j} \mathbf{s}_j'$ . As  $\lim_{c \rightarrow +\infty} (\mathbf{s}_j + c(\mathbf{s}_{0,j} + \delta(w_j))) = \mathbf{x}_j$ , Lemma 6 proves that there exists an integer  $c_0 \geq 0$  such that for any integer  $c \geq c_0$  we have  $(\mathbf{s}_j + c(\mathbf{s}_{0,j} + \delta(w_j))) \xrightarrow{\sigma_j} \mathbf{s}_j'$ . As  $\xi$  is a solution of the characteristic system we get  $\mathbf{s}_j + \delta(\sigma_j) = \mathbf{s}_j'$ . Moreover, as  $\xi_0$  is a solution of the homogeneous characteristic system we get  $\mathbf{s}_{0,j} + \delta(w_j \sigma_{0,j} w_j') = \mathbf{s}_{0,j}'$ . In particular we deduce that  $(\mathbf{s}_j + c\mathbf{s}_{0,j}) + c\delta(w_j) + \delta(\sigma_j) = (\mathbf{s}_j' + c\mathbf{s}_{0,j}') - c\delta(w_j') - c\delta(\sigma_{0,j})$ . We deduce that for any  $c \geq c_0$  we have:

$$(\mathbf{s}_j + c\mathbf{s}_{0,j}) \xrightarrow{w_j^c \sigma_j \sigma_{0,j}' (w_j')^c} \mathbf{s}_j' + c\mathbf{s}_{0,j}'$$

Therefore there exists a word in  $\mathcal{L}(\mathcal{U})$  associated to  $\xi + c\xi_0$  for any  $c \geq c_0$ . In particular we have proved that  $\mathcal{L}(\mathcal{U}) \neq \emptyset$ .

## 4.2 Semi-pseudo-linear Reachability Sets

In this section we prove that  $\text{post}_V^*(S) \cap S'$  and  $S \cap \text{pre}_V^*(S')$  are semi-pseudo-linear for any semi-linear sets  $S, S' \subseteq \mathbb{N}^n$ .

Let us reduce our problem to the forward case with  $S = \{\mathbf{b}\}$  and  $S' = \mathbf{b} + Z^*$  where  $Z$  is a set of periods. Since  $\text{post}_V^*(X) = \text{pre}_V^*(X)$  for any set  $X \subseteq \mathbb{N}^n$  where  $-\mathcal{V} = (\Sigma, n, -\delta)$ , the problem reduces to prove that  $\text{post}_V^*(S) \cap S'$  is semi-pseudo-linear. Note also that a semi-linear set is a finite union of linear sets. As  $\text{post}_V^*(X_1 \cup \dots \cup X_k) = \text{post}_V^*(X_1) \cup \dots \cup \text{post}_V^*(X_k)$  for any  $X_1, \dots, X_k \subseteq \mathbb{N}^n$ , we have reduced the problem to prove that  $\text{post}_V^*(S) \cap S'$  is semi-pseudo-linear for any linear sets  $S, S'$ . Let us consider a linear set  $S = \mathbf{b} + P^*$  where  $\mathbf{b} \in \mathbb{N}^n$  and  $P \subseteq \mathbb{N}^n$  is a finite set of periods. Without loss of generality we can assume that  $P \cap \Sigma = \emptyset$ . Let us consider the VAS  $\mathcal{V}' = (\Sigma', n, \delta')$  where  $\Sigma' = \Sigma \cup P$  and  $\delta'$  extends  $\delta$  by  $\delta(\mathbf{p}) = \mathbf{p}$  for any  $\mathbf{p} \in P$ . We observe that  $\text{post}_V^*(S) = \text{post}_{\mathcal{V}'}^*(\{\mathbf{b}\})$ . In particular we can assume that  $S = \{\mathbf{b}\}$ . We have proved the proposed reduction.

So, let us consider two configurations  $\mathbf{b}, \mathbf{b}' \in \mathbb{N}^n$ , a set of periods  $Z \subseteq \mathbb{N}^n$  and let us prove that  $\text{post}_V^*(\{\mathbf{b}\}) \cap (\mathbf{b}' + Z^*)$  is semi-pseudo-linear. We can assume that  $Z \cap \Sigma = \emptyset$ . As expected, we consider the VAS  $\mathcal{V}_Z$  obtained from  $\mathcal{V}$  by considering the alphabet  $\Sigma \cup Z$  and the displacement function that extends  $\delta$  by  $\delta(\mathbf{z}) = -\mathbf{z}$  for any  $\mathbf{z} \in Z$ . We also consider the displacement function  $\delta_Z$  also defined over  $\Sigma \cup Z$  by  $\delta_Z(a) = \mathbf{0}$  if  $a \in \Sigma$  and  $\delta_Z(\mathbf{z}) = \mathbf{z}$  if  $\mathbf{z} \in Z$ . Observe that we have the following equality:

$$\text{post}_V^*(\{\mathbf{b}\}) \cap (\mathbf{b}' + Z^*) = \mathbf{b}' + \delta_Z(\mathcal{L}(\mathbf{b}, \mathcal{V}_Z, \mathbf{b}'))$$

From theorem 1, it is sufficient to prove that  $\delta_Z(\mathcal{L}(\mathcal{U}))$  is pseudo-linear for any perfect MGVS  $\mathcal{U}$  for  $(\mathbf{b}, \mathcal{V}_Z, \mathbf{b}')$ . So let us consider such a perfect MGVS  $\mathcal{U}$  of the following form:

$$\mathcal{U} = (\mathbf{m}_0, G_0, \mathbf{x}_0, \mathbf{m}_0'), a_1, \dots, a_k, (\mathbf{m}_k, G_k, \mathbf{x}_k, \mathbf{m}_k')$$

Given a solution  $\xi = ((\mathbf{s}_j)_j, (\mu_{j,t})_{j,t}, (\mathbf{s}_j')_j)$  of the characteristic system and a solution  $\xi_0 = ((\mathbf{s}_{0,j})_j, (\mu_{0,j,t})_{j,t}, (\mathbf{s}_{0,j}')_j)$  of the homogeneous characteristic system, we consider the vectors  $\beta_0(\xi_0)$  and  $\beta(\xi)$  defined by the following equalities:

$$\begin{aligned} \beta(\xi) &= \delta_Z(a_1 \dots a_k) + \sum_{\substack{\mathbf{z} \in Z \\ 0 \leq j \leq k \\ t=(q,\mathbf{z},q') \in T_j}} \mu_{j,t} \mathbf{z} \\ \beta_0(\xi_0) &= \sum_{\substack{\mathbf{z} \in Z \\ 0 \leq j \leq k \\ t=(q,\mathbf{z},q') \in T_j}} \mu_{0,j,t} \mathbf{z} \end{aligned}$$

We observe that  $\xi + \xi_0$  is a solution of the characteristic system that satisfies  $\beta(\xi + \xi_0) = \beta(\xi) + \beta_0(\xi_0)$ . Moreover, note that if  $\xi$  is associated to a word  $\sigma \in \mathcal{L}(\mathcal{U})$  then  $\delta_Z(\sigma) = \beta(\xi)$ .

Intuitively, the linearizator  $P$  of  $\delta_Z(\mathcal{L}(\mathcal{U}))$  is obtained from the homogeneous characteristic system of  $\mathcal{U}$ . We denote by  $H$  the non-negative solutions of the characteristic system and we denote by  $H_0$  the non-negative solutions of the homogeneous characteristic system. Observe that  $H = \min(H) + H_0$  and  $H_0 = \min(H_0 \setminus \{\mathbf{0}\})^*$ .

We consider the following set of periods:

$$P = \beta_0(\min(H_0 \setminus \{\mathbf{0}\}))$$

Let us first prove that there exists  $\xi \in H$  and  $\xi_0 \in H_0$  such that  $\delta_Z(\mathcal{L}(\mathcal{U})) \subseteq \beta(\xi) - \beta_0(\xi_0) + P^*$ . Since  $\delta_Z(\mathcal{L}(\mathcal{U})) \subseteq \beta(H)$ , it is sufficient to prove the inclusion  $\beta(H) \subseteq \beta(\xi) - \beta_0(\xi_0) + P^*$ . As the MGVS  $\mathcal{U}$  is perfect the set  $H$  is non empty. Let us consider the set  $I$  of components  $i$  such that  $\xi[i]$  is independent of  $\xi \in H$ . As the MGVS is perfect we deduce that for any integer  $c \geq 0$  there exists  $\xi \in H$  such that  $\xi[i] \geq c$  for any  $i \notin I$ . As  $\min(H)$  is finite, we deduce that there exists  $\xi \in H$  such that  $\xi \geq \xi'$  for any  $\xi' \in \min(H)$ . In particular  $\xi_0 = \sum_{\xi' \in \min(H)} (\xi - \xi')$  is in  $H_0$ . Let us show that  $\xi'' + \xi_0 - \xi \in H_0$  for any  $\xi'' \in H$ . There exists  $\xi' \in \min(H)$  such that  $\xi' \leq \xi''$ . Thus  $\xi'' + \xi_0 - \xi = (\xi'' - \xi') + \xi_0 - (\xi - \xi')$ . From  $\xi'' - \xi' \in H_0$  and  $\xi_0 - (\xi - \xi') \in H_0$  we deduce that  $\xi'' + \xi_0 - \xi \in H_0$ . We have proved that  $H \subseteq \xi - \xi_0 + H_0$ . Finally, from  $H_0 = \min(H_0 \setminus \{\mathbf{0}\})^*$ , we deduce the following inclusion:

$$\delta_Z(\mathcal{L}(\mathcal{U})) \subseteq \beta(\xi) - \beta_0(\xi_0) + P^*$$

Now, let us consider a set  $R_0 = \{\xi_1, \dots, \xi_d\}$  of attractors of  $H_0$ . We are going to prove that there exists a vector  $\mathbf{x}_0$  such that  $\mathbf{x}_0 + \beta_0(R_0^*) \subseteq \delta_Z(\mathcal{L}(\mathcal{U}))$ . We first prove the following lemma.

LEMMA 8. *For any attractor  $\xi_1 = ((\mathbf{s}_{1,j})_j, (\mu_{1,j,t})_{j,t}, (\mathbf{s}_{1,j}')_j)$  of  $\min(H_0 \setminus \{\mathbf{0}\})$  there exists a cycle  $\pi_{1,j} = (\mathbf{x}_j \xrightarrow{\sigma_{1,j}}_{G_j} \mathbf{x}_j)$  such that  $\mu_{1,j,t} = |\pi_{1,j}|_t$  for any  $t \in T_j$  and any  $0 \leq j \leq k$ .*

PROOF. Since  $\mathcal{U}$  is perfect, for any  $t \in T_j$ , there exists a solution  $\xi_0 = ((\mathbf{s}_{0,j})_j, (\mu_{0,j,t})_{j,t}, (\mathbf{s}_{0,j}')_j)$  in  $H_0$  such that  $\mu_{0,j,t} \geq 1$ . As  $H_0$  is the monoid generated by  $\min(H_0 \setminus \{\mathbf{0}\})$ ,



there exists  $\xi_0 \in \min(H_0 \setminus \{\mathbf{0}\})$  satisfying the same property. Lemma 1 shows that  $\xi_1 = ((\mathbf{s}_{i,j})_j, (\mu_{i,j,t})_{j,t}, (\mathbf{s}'_{i,j})_j)$  is a sum over all solutions  $\xi_0 \in \min(H_0 \setminus \{\mathbf{0}\})$  of terms of the form  $\lambda \xi_0$  where  $\lambda > 0$  is a rational value that naturally depends on  $\xi_0$ . In particular we deduce that  $\mu_{i,j,t} \geq 1$  for any  $t \in T_j$  and for any  $0 \leq j \leq k$ . Lemma 5 shows that there exists a cycle  $\pi_{i,j} = (\mathbf{x}_j \xrightarrow{\sigma_{i,j}}_{G_j} \mathbf{x}_j)$  such that  $\mu_{i,j,t} = |\pi_{i,j}|_t$  for any  $t \in T_j$  and any  $1 \leq j \leq k$ .  $\square$

Now, let us consider a solution  $\xi$  of the characteristic system and a solution  $\xi_0$  of the homogeneous characteristic system satisfying the same properties that the ones given at the end of the previous section. As  $\lim_{c \rightarrow +\infty} (\mathbf{s}_j + c(\mathbf{s}_{0,j} + \delta(w_j))) = \mathbf{x}_j$ , lemma 6 proves that by replacing  $c_0$  by a larger integer, we can assume that  $(\mathbf{s}_j + c(\mathbf{s}_{0,j} + \delta(w_j))) \xrightarrow{\sigma_{i,j}}_{\mathcal{V}}$  for any  $c \geq c_0$ , for any  $0 \leq j \leq k$  and for any  $1 \leq i \leq d$ . Let us consider a sequence  $n_1, \dots, n_d \in \mathbb{N}$  and an integer  $c \geq c_0$ . Using the same method than the one previously used for proving that  $\mathcal{L}(\mathcal{U}) \neq \emptyset$  for any perfect MGVS  $\mathcal{U}$ , we observe that for any  $0 \leq j \leq k$  we have:

$$\begin{aligned} & \mathbf{s}_j + c\mathbf{s}_{0,j} + \sum_{i=1}^d n_i \mathbf{s}_{i,j} \\ & \xrightarrow{w_j^c \sigma_j \sigma_{1,j}^{n_1} \dots \sigma_{d,j}^{n_d} \sigma_{0,j}^c (w_j')^c} \mathcal{V} \\ & \mathbf{s}'_j + c\mathbf{s}'_{0,j} + \sum_{i=1}^d n_i \mathbf{s}'_{i,j} \end{aligned}$$

We have proved that there exists a word  $\sigma \in \mathcal{L}(\mathcal{U})$  associated with  $\xi + c_0 \xi_0 + \sum_{i=1}^d n_i \xi_i$ . By applying  $\beta$  to the previous tuple, we deduce that  $\delta_Z(\sigma) = \mathbf{x}_0 + \sum_{i=1}^d n_i \beta_0(\mathbf{x}_i)$  where  $\mathbf{x}_0 = \beta(\xi) + c\beta_0(\xi_0)$ . We have proved the following inclusion:

$$\mathbf{x}_0 + \beta_0(R_0^*) \subseteq \delta_Z(\mathcal{L}(\mathcal{U}))$$

The following lemma shows that  $P$  is a linearizator of  $\delta_Z(\mathcal{L}(\mathcal{U}))$ .

LEMMA 9. *For any set of attractors  $R \subseteq \mathcal{A}(P^*)$  there exists a finite set of attractors  $R_0 \subseteq \mathcal{A}(H_0)$  and a vector  $\mathbf{r} \in R^*$  such that:*

$$\mathbf{r} + R^* \subseteq \beta_0(R_0^*)$$

PROOF. Let us consider a set  $R = \{\mathbf{r}_1, \dots, \mathbf{r}_d\}$  of attractors of  $P^*$ . As  $\mathbf{r}_i \in P^*$ , there exists  $\xi_i \in H_0$  such that  $\mathbf{r}_i = \beta_0(\xi_i)$ . Lemma 1 shows that any  $\mathbf{r}_i \in R$  is a sum of vectors of the form  $\lambda \beta_0(\xi_0)$  over all  $\xi_0 \in \min(H_0 \setminus \{\mathbf{0}\})$  where  $\lambda > 0$  is a rational value that naturally depends on  $\xi_0$ . Thus there exists an integer  $N_i \geq 1$  larger enough and an attractor  $\xi'_i$  of  $H_0$  such that  $N_i \mathbf{r}_i = \beta_0(\xi'_i)$ . Let us consider the set  $R_0$  of solutions of the form  $\xi'_i + \lambda_i \xi_i$  where  $\lambda_i$  is an integer such that  $0 \leq \lambda_i < N_i$ . As  $\xi'_i$  is an attractor of  $H_0$  and  $\xi_i \in H_0$  we deduce that  $\xi'_i + \lambda_i \xi_i$  is also an attractor of  $H_0$ . We have proved that  $R_0 \subseteq \mathcal{A}(H_0)$ . Let us consider the vector  $\mathbf{r} = \sum_{i=1}^d N_i \mathbf{r}_i$  and let us prove that  $\mathbf{r} + R^* \subseteq \beta_0(R_0^*)$ . Note that  $\mathbf{r} = \beta_0(\sum_{i=1}^d \xi'_i)$ . Consider  $\mathbf{r}' \in R^*$ . There exists a sequence  $(\mu_i)_{1 \leq i \leq d}$  of integers in  $\mathbb{N}$  such that  $\mathbf{r}' = \sum_{i=1}^d \mu_i \mathbf{r}_i$ . The Euclidean division of  $\mu_i$  by  $N_i$  shows that  $\mu_i = \mu'_i + N_i \lambda_i$  where  $\lambda_i \in \mathbb{N}$  and  $\mu'_i$  is an

integer such that  $0 \leq \mu'_i < N_i$ . From  $N_i \mathbf{r}_i = \beta_0(\xi'_i)$  we deduce that  $\mathbf{r} + \mathbf{r}' = \beta_0(\sum_{i=1}^d \lambda_i \xi'_i + \sum_{i=1}^d \xi'_i + \mu'_i \xi_i)$ . Observe that  $\xi'_i$  and  $\xi'_i + \mu'_i \xi_i$  are both in  $R_0$ . We have proved that  $\mathbf{r} + R^* \subseteq \beta_0(R_0^*)$ .  $\square$

Therefore, we have proved the following theorem:

THEOREM 2. *For any pair  $S, S' \subseteq \mathbb{N}^n$  of semi-linear sets, the sets  $\text{post}_{\mathcal{V}}^*(S) \cap S'$  and  $S \cap \text{pre}_{\mathcal{V}}^*(S')$  are semi-pseudo-linear.*

## 5. SEMI-LINEAR SEPARATORS

In this section we prove that there exists a semi-linear separator for any pair of semi-linear separable pair.

Given a pair  $(S, S')$  of separable sets of configurations, the set  $D = \mathbb{N}^n \setminus (S \cup S')$  is called the *domain* of  $(S, S')$ . Note that a separable pair  $(S, S')$  with an empty domain  $D$  is a separator even if there exists separators with a non-empty domain.

The semi-linear separator for a semi-linear separable pair  $(S_0, S'_0)$  is obtained inductively. We build a non-decreasing sequence  $(S_j, S'_j)_{j \geq 0}$  of semi-linear separable sets starting from the initial semi-linear separable pair  $(S_0, S'_0)$  such that the dimension of the domain  $D_j = \mathbb{N}^n \setminus (S_j \cup S'_j)$  is strictly decreasing. In order to obtain this sequence, observe that it is sufficient to show that for any semi-linear separable pair  $(S_0, S'_0)$  of configuration sets with a non-empty domain  $D_0$ , there exists a semi-linear separable pair  $(S, S') \supseteq (S_0, S'_0)$  with a domain  $D$  such that  $\dim(D) < \dim(D_0)$ .

We first define a set  $S'$  that over-approximates  $S'_0$  and such that  $(S_0, S')$  remains separable. As  $S_0$  and  $D_0$  are semi-linear, the main result of section 4 shows that  $\text{post}_{\mathcal{V}}^*(S_0) \cap D_0$  is equal to a finite union of pseudo-linear sets  $X_1, \dots, X_k$ . Let us consider some linearizations  $L_1, \dots, L_k$  of these pseudo-linear sets and let us define the following semi-linear set  $S'$ . We observe that  $\text{post}_{\mathcal{V}}^*(S_0) \cap S' = \emptyset$  since  $\text{post}_{\mathcal{V}}^*(S_0) \cap S'_0 = \emptyset$  and  $\text{post}_{\mathcal{V}}^*(S_0) \cap D_0 \subseteq \bigcup_{j=1}^k L_j$ . Thus  $\text{post}_{\mathcal{V}}^*(S_0) \cap \text{pre}_{\mathcal{V}}^*(S') = \emptyset$  and we have proved that  $S'$  contains  $S'_0$  and  $(S_0, S')$  is separable.

$$S' = S'_0 \cup (D_0 \setminus (\bigcup_{j=1}^k L_j))$$

Now we define symmetrically a set  $S$  that over-approximates  $S_0$  and such that  $(S, S')$  remains separable. As  $D_0$  and  $S'$  are semi-linear, the main result proved in section 4 shows that  $D_0 \cap \text{pre}_{\mathcal{V}}^*(S')$  is equal to a finite union of pseudo-linear sets  $X'_1, \dots, X'_{k'}$ . Let us consider some linearizations  $L'_1, \dots, L'_{k'}$  of these pseudo-linear sets and let us define the following semi-linear set  $S$ . Once again, note that  $S \cap \text{pre}_{\mathcal{V}}^*(S') = \emptyset$ . Thus  $S$  contains  $S_0$  and  $(S, S')$  is separable.

$$S = S_0 \cup (D_0 \setminus (\bigcup_{j=1}^{k'} L'_j))$$

Let  $D$  be the domain of the separable pair  $(S, S')$ . From  $D_0 = \mathbb{N}^n \setminus (S_0 \cup S'_0)$ , we get the following equality.

$$D = D_0 \cap \left( \bigcup_{\substack{1 \leq j_1 \leq k \\ 1 \leq j_2 \leq k'}} (L_{j_1} \cap L'_{j_2}) \right)$$

From  $X_{j_1}, X'_{j_2} \subseteq D_0$  we get  $\max\{\dim(X_{j_1}), \dim(X'_{j_2})\} \leq \dim(D_0)$ . As  $X_{j_1} \subseteq \text{post}_V^*(S_0) \subseteq \text{post}_V^*(S)$  and  $X'_{j_2} \subseteq \text{pre}_V^*(S')$  and  $(S, S')$  is separable, we deduce that  $X_{j_1}$  and  $X'_{j_2}$  are two pseudo-linear sets with an empty intersection. From the main result proved in section 3, we get  $\dim(L_{j_1} \cap L'_{j_2}) < \max\{\dim(X_{j_1}), \dim(X'_{j_2})\}$ . We deduce  $\dim(D) < \dim(D_0)$ . We have proved the following theorem.

**THEOREM 3.** *There exists a semi-linear separator for any pair of semi-linear separable sets.*

## 6. CONCLUSION

We have proved the termination of the algorithm **Reachability**. Even though the proof is based on the classical KLMST decomposition, its complexity does not depend on this decomposition. In fact, the complexity of this algorithm depends on the size of the minimal pair of Presburger formulas denoting a separator for a separable pair  $(\{s\}, \{s'\})$ . This algorithm is the *very first one* that does not require the KLMST decomposition. In particular, this algorithm is the first candidate to obtain a precise (eventually elementary) upper-bound complexity for the VAS reachability problem.

We left as an open question the problem of computing a lower bound and an upper bound of the size of a pair of Presburger formulas denoting a separator for a separable pair  $(\{s\}, \{s'\})$ . Note that the VAS exhibiting a large (Ackermann size) but finite reachability set given in [4] does not directly provide a lower-bound for this size since separators can over-approximate reachability sets.

We also left as an open question the problem of adapting such an algorithm to obtain a complete *Counter Example Guided Abstract Refinement* approach [1] for the VAS reachability problem based on *interpolants* [6] for  $\text{FO}(\mathbb{N}, +, \leq)$ . In practice, such an algorithm should be more efficient than the enumeration-based algorithm provided in this paper.

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## 7. REFERENCES

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