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Multihomogeneous polynomial decomposition using moment matrices

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Abstract

In this paper, we address the problem of tensor decomposition which can be seen as a generalisation of Singular Value Decomposition for matrices. We consider general multilinear and multihomogeneous tensors. We show how to reduce the problem to a truncated moment matrix problem and give a new criterion for flat extension of Quasi-Hankel matrices. We connect this criterion to the commutation characterisation of border bases. A new algorithm is described. It applies for general multihomogeneous tensors, extending the approach of J.J. Sylvester on binary forms. An example illustrates the algebraic operations involved in this approach and how the decomposition can be recovered from eigenvector computation.

1 Introduction

Tensors are objects which appear in many context and applications. The most famous type of tensors corresponds to matrices which are tensors of order two. But in many problems, higher order tensors are naturally used to collect information which depend on more than two variables. Typically, these data could be observations of some experimentation or of a physical phenomena that depends on several parameters. These observations are stored in a structure called a tensor, according to the dimensional parameters (or modes) of the problem.

The tensor decomposition problem consists to decompose the tensor (e.g. the set of observations) into a minimal sum of indecomposable tensors (i.e. tensors of rank 1). Such a decomposition which is independent of the coordinate system allows to extract geometric or invariant properties associated to the observations. For this reason, the tensor decomposition problem has a large impact in many applications. The first well known case for matrices is related to Singular Value Decomposition with applications e.g. to Principal Component Analysis. Its extension to higher order tensors appears in Electrical Engineering [57], in Signal processing [23], [17], in Antenna Array Processing [27] [15] or Telecommunications [59], [14], [54], [30], [26], in Chemometrics [9] or Psychometrics [37], in Data Analysis [19], [12], [28], [36], [55], but also in more theoretical domains such as Arithmetic complexity [38] [7], [56], [39]. Further numerous applications of tensor decompositions may be found in [17], [55].

From a mathematical point of view, the tensors that we will consider are elements of $\mathcal{T} := S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$ where $\delta_i \in \mathbb{N}$, E_i are vector spaces of dimension $n_i + 1$ over a field \mathbb{K} (which is of characteristic 0 and algebraically closed), and $S^{\delta_i}(E_i)$ is the δ_i^{th} symmetric power of E_i . The set of tensors of rank 1 form a projective variety which is called the Veronese variety when $k = 1$ or the Segre variety when $\delta_i = 1, i = 1, \dots, k$. We will call it hereafter the Segre-Veronese variety of $\mathbb{P}(\mathcal{T})$ and denote it $\Xi(\mathcal{T})$. The set of tensors which are the linear combinations of r elements of the Segre-Veronese variety are those which admits a decomposition with at most r terms of rank 1 (i.e.

in $\Xi(\mathcal{T})$). The closure of this set is called the r -secant variety and denoted $\Xi_r(\mathcal{T})$. More precise definitions of these varieties will be given in Sec. 2.3.

Decomposing a tensor T consists in finding the minimal r such that this tensor is a sum of r tensors of rank 1. This minimal r is called the rank of T . By definition, a tensor of rank r is in the secant variety $\Xi_r(\mathcal{T})$. Thus analysing the properties of these secant varieties and their characterisation helps determining tensor ranks and decompositions.

The case where $k = 2$ and $\delta_1 = \delta_2 = 1$ corresponds to the matrix case which is well known. The rank of a matrix seen as a tensor of order $k = 2$ is its usual rank. The case where $k = 1$ and $\delta_1 = 2$ corresponds to the case of quadratic forms matrices and is also well understood. The rank of the symmetric tensor is the usual rank of the associated symmetric matrix. The case where $k = 1$, $\delta_1 \in \mathbb{N}$ and $n_1 = 1$ corresponds to binary forms, which has been analyzed by J.J. Sylvester in [58]. A more complete description in terms of secant varieties is given in [43].

On our knowledge if $k > 1$ and if at least one of the δ_i 's is bigger than 1 then there is no specific result in the literature on the defining ideal of secant varieties of Segre-Veronese varieties $\Xi(S^{\delta_1}(E_1) \otimes \cdots \otimes S^{\delta_k}(E_k))$ except for [13] where the authors conjecture that when $\Xi_r(S^{\delta_1}(E_1) \otimes S^{\delta_2}(E_2))$ is a defective hypersurface then its defining equation is a determinantal equation.

On the case of the secant varieties of Veronese varieties (i.e. if $k = 1$ and $\delta_1 > 1$) then it is a classical result that if $\dim(E_1) = 2$ then the ideal of $\Xi_s(S^d(\mathbb{K}^2))$ is generated by the $(s+1) \times (s+1)$ minors of the Hankel matrices (the results is due to Gundelfinger, see e.g. [35]). In [35] the ideals of the following varieties are also described: $\Xi_r(S^{2\delta}(\mathbb{K}^3))$ if $r \leq \binom{\delta+1}{2}$ and $\Xi_r(S^{2\delta+1}(\mathbb{K}^3))$ if $r \leq \binom{\delta+1}{2} + 1$. Another classical result is that the defining ideals for $\Xi_s(S^2(\mathbb{K}^{n+1}))$ are given by the $(s+1)$ -minors of a generic symmetric matrix of size $(n+1) \times (n+1)$. The equation of the hypersurface $\Xi_3(S^3(\mathbb{K}^3))$ is classically known as the Aronhold invariant (see [49] for a modern description) but the equations for $\Xi_3(S^3(\mathbb{K}^{n+1}))$ were found in 2010 in [42]. In [52] the ideals of $\Xi_3(S^4(\mathbb{K}^3))$ and of $\Xi_4(S^4(\mathbb{K}^3))$ are described; while the cases $\Xi_3(S^d(\mathbb{K}^{n+1}))$ and $\Xi_4(S^d(\mathbb{K}^3))$ for $d > 4$ are described in [42]. The last classical result that we quote is $\Xi_5(S^4(\mathbb{K}^3))$ whose defining ideal was found by Clebsch (we again refer to [35] for a good description); the cases $\Xi_5(S^d(\mathbb{K}^3))$ for $d \geq 6$ are described in [42]. In this last quoted paper the authors give also the ideal of the following varieties: $\Xi_r(S^5(\mathbb{K}^3))$ for $r \leq 6$, $\Xi_6(S^d(\mathbb{K}^3))$ for $d \geq 6$, $\Xi_r(S^6(\mathbb{K}^3))$ for $r = 7, 8, 9$ ($r = 9$ is classical), $\Xi_r(S^7(\mathbb{K}^3))$ $r \geq 10$. We also quote [43] for a modern approach to equations of secant varieties using representation theory.

About the case of secant varieties of Segre varieties (i.e. $\delta_i = 1$ for $i = 1, \dots, k$) the only obvious case is the 2 factors Segre: since its s -th secant varieties parametrizes rank s matrices then the order $s+1$ minors of a generic matrix of indeterminates give the equations of $\Xi_s(E_1 \otimes E_2)$. In [31] it was conjectured that for $s = 2$ the 3×3 minors coming from the flattenings are the generators of $\Xi_2(E_1 \otimes \cdots \otimes E_k)$. This conjecture was proved in some cases: $\Xi_2(E_1 \otimes E_2 \otimes E_3)$ (in [40]), $\Xi_2(E_1 \otimes E_2 \otimes E_3 \otimes E_4)$ (in [44]) and up to the 5 factors Segre in [2]. Actually a set of equations that defines $\Xi_2(E_1 \otimes \cdots \otimes E_k)$ set theoretically for any k are known (see [40]). In [13] it is also shown by performing examples that the ideal of the secant varieties of Segre variety cannot always come from the minors of the flattenings. Nevertheless they proved that for $\prod_{i=1}^t (\dim E_i) - \sum_{i=1}^t (\dim E_i - 1) \leq s \leq \min\{\dim V, \prod_{i=1}^t (\dim E_i) - 1\}$ then the ideal of $\Xi_s(E_1 \otimes \cdots \otimes E_t \otimes V)$ is the same of the ideal of $\Xi_s(W \otimes V)$, with $\dim W = \prod_{i=1}^t (\dim E_i)$ and it is generated by the $(s+1) \times (s+1)$ minors of an $(\dim V) \times (\prod_{i=1}^t (\dim E_i))$ matrix of indeterminates. To complete our list we quote again [40] for the ideals of $\Xi_4(V^{\otimes 3})$ and of $\Xi_3(U \otimes V \otimes W)$ with $\dim U = 2$, $\dim V = 3$ and $\dim W = 4$. Moreover in [41] the authors give a set of equations defining set theoretically $\Xi_3(E_1 \otimes E_2 \otimes E_3)$ and $\Xi_4(E_1 \otimes E_2 \otimes E_3)$ for $\dim E_i \geq 3$, $i = 1, 2, 3$. Another set theoretical result is due to Friedland that gives equations for $\Xi_4(W^{\otimes 3})$ with $\dim W = 4$ giving a set theoretical answer to the ‘‘salmon prize’’ (offered by E. Allman in 2007). The last known secant varieties of Segre varieties whose ideals are described, on our knowledge, $\Xi_k(U \otimes V \otimes V)$ and $\Xi_3(E_1 \otimes E_2 \otimes E_3)$ with $\dim U = 2$ for any V, E_1, E_2, E_3 (see [44]). The first method to compute such a decomposition besides the case of matrices or quadratic forms which may go back to the Babylonians, is due to Sylvester for binary forms [58]. Using apolarity, kernels of catalecticant matrices are computed degree by degree until a polynomial with simple roots is found. See also [18], [35]. An extension of this approach for symmetric tensors has been analyzed

in [35], and yields a decomposition method in some cases (see [35][p. 187]). Some decomposition methods are also available for specific degrees and dimensions, e.g. using invariant theory [22]. In [6], there is a simplified version of the Sylvester algorithm that uses the mathematical interpretation of the problem in terms of secant varieties of rational normal curves. The same approach is used in [6] to give algorithms for the decompositions of symmetric tensors belonging to $\Xi_2(S^d(E))$ and to $\Xi_3(S^d(E))$. In [4] a complete rank stratification of $\Xi_4(S^d(E))$ is given.

In [8], Sylvester's approach is revisited from an affine point of view and a general decomposition method based on a flat extension criteria is described. In the current paper, we extend this method to more general tensor spaces including classical multilinear tensors and multihomogeneous tensors. We give a new and more flexible criterion for the existence of a decomposition of a given rank, which extends the result in [46] and the characterisation used in [8]. This criterion is a rank condition of an associated Hankel operator. It is used in an algorithm which checks degree by degree if the roots deduced from the kernel of the Hankel operator are simple.

In Sec. 2, we recall the notations, the geometric point related to secants of Segre and Veronese varieties, and the algebraic point of view based on moment matrices. In Sec. 3, we describe the algorithm and the criterion used to solve the truncated moment problem. In Sec. 4, an example of tensor decompositions from Antenna processing illustrates the approach.

2 Duality, moment matrices and tensor decomposition

2.1 Notation and preliminaries

Let \mathbb{K} be an algebraically closed field (e.g. $\mathbb{K} = \mathbb{C}$ the field of complex numbers). We assume that \mathbb{K} is of characteristic 0. For a vector space E , its associated projective space is denoted $\mathbb{P}(E)$. For $\mathbf{v} \in E - \{0\}$ its class in $\mathbb{P}(E)$ is denoted $\bar{\mathbf{v}}$. Let \mathbb{P}^n be the projective space of $E := \mathbb{K}^{n+1}$. For a subset $F = \{f_1, \dots, f_m\}$ of a vector-space (resp. ring) R , we denote by $\langle F \rangle$ (resp. (F)) the vector space (resp. ideal) generated by F in R .

We consider hereafter the symmetric δ -th power $S^\delta(E)$ where E is a vector space of basis x_0, \dots, x_n . An element of $S^\delta(E)$ is a homogeneous polynomial of degree $\delta \in \mathbb{N}$ in the variables $\mathbf{x} = (x_0, \dots, x_n)$. For $\mathbf{x}_1 = (x_{0,1}, \dots, x_{n_1,1}), \dots, \mathbf{x}_k = (x_{0,k}, \dots, x_{n_k,k})$, $S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$ (with $E_i = \langle x_{0,i}, \dots, x_{n_i,i} \rangle$) is the vector space of polynomials multihomogeneous of degree δ_i in the variables \mathbf{x}_i .

Hereafter, we will consider the deshomogenisation of elements in $S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$, obtained by setting $x_{0,i} = 1$ for $i = 1, \dots, k$. We denote by $R_{\delta_1, \dots, \delta_k}$ this space, where $R = \mathbb{K}[\underline{\mathbf{x}}_1, \dots, \underline{\mathbf{x}}_k]$ is the space of polynomials in the variables $\underline{\mathbf{x}}_1 = (x_{1,1}, \dots, x_{n_1,1}), \dots, \underline{\mathbf{x}}_k = (x_{1,k}, \dots, x_{n_k,k})$.

For $\alpha_i = (\alpha_{1,i}, \dots, \alpha_{n_i,i}) \in \mathbb{N}^{n_i}$ ($i = 1, \dots, k$), let $\underline{\mathbf{x}}_i^{\alpha_i} = \prod_{j=1}^{n_i} x_{j,i}^{\alpha_{j,i}}$, $|\alpha_i| = \sum_{j=1}^{n_i} \alpha_{j,i}$, and $\underline{\mathbf{x}}^\alpha = \prod_{j=1}^{n_i} \underline{\mathbf{x}}_j^{\alpha_j}$.

An element f of $R_\delta = R_{\delta_1, \dots, \delta_k}$ is represented as

$$f = \sum_{\alpha = (\alpha_1, \dots, \alpha_k); |\alpha_i| \leq \delta_i} f_\alpha \underline{\mathbf{x}}_1^{\alpha_1} \dots \underline{\mathbf{x}}_k^{\alpha_k}.$$

The dimension of $R_\delta := R_{\delta_1, \dots, \delta_k}$ is $n_{\delta_1, \dots, \delta_k; n_1, \dots, n_k} = \prod_{i=1}^k \binom{n_i + \delta_i}{\delta_i}$. For $\delta \in \mathbb{N}, \alpha \in \mathbb{N}^n$ with $|\alpha| \leq \delta$, let $\binom{\delta}{\alpha} = \frac{\delta!}{\alpha_1! \dots \alpha_n! (\delta - |\alpha|)!}$. We define the apolar inner product on $R_{\delta_1, \dots, \delta_k}$ by $\langle f | g \rangle = \sum_{|\alpha_i| \leq \delta_i} f_\alpha g_\alpha \binom{\delta_1}{\alpha_1} \dots \binom{\delta_k}{\alpha_k}$.

The dual space of a \mathbb{K} -vector space E is denoted $E^* = \text{Hom}_{\mathbb{K}}(E, \mathbb{K})$. It is the set of \mathbb{K} -linear forms from E to \mathbb{K} . A basis of the dual space R_δ^* , is given by the set of linear forms that compute the coefficients of a polynomial in the monomial basis $(\underline{\mathbf{x}}^\alpha)_{\alpha \in \mathbb{N}^{n_1} \times \dots \times \mathbb{N}^{n_k}; |\alpha_i| \leq \delta_i}$. We denote it by $(\mathbf{d}^\alpha)_{\alpha \in \mathbb{N}^{n_1} \times \dots \times \mathbb{N}^{n_k}; |\alpha_i| \leq \delta_i}$. We identify R^* with the (vector) space of formal power series $\mathbb{K}[[\mathbf{d}]] = \mathbb{K}[[\mathbf{d}_1, \dots, \mathbf{d}_k]] = \mathbb{K}[[d_{1,1}, \dots, d_{n_1,1}, \dots, d_{1,k}, \dots, d_{n_k,k}]]$. Any element $\Lambda \in R^*$ can be decomposed as

$$\Lambda = \sum_{\alpha \in \mathbb{N}^{n_1} \times \dots \times \mathbb{N}^{n_k}} \Lambda(\mathbf{x}^\alpha) \mathbf{d}^\alpha.$$

Typical elements of R^* are the linear forms that correspond to the evaluation at a point $\zeta = (\zeta_1, \dots, \zeta_i) \in \mathbb{K}^{n_1} \times \dots \times \mathbb{K}^{n_k}$:

$$\begin{aligned} \mathbf{1}_\zeta &: R \rightarrow \mathbb{K} \\ p &\mapsto p(\zeta) \end{aligned}$$

The decomposition of $\mathbf{1}_\zeta$ in the basis $\{\mathbf{d}^\alpha\}_{\alpha \in \mathbb{N}^{n_1} \times \dots \times \mathbb{N}^{n_k}}$ is

$$\mathbf{1}_\zeta = \sum_{\alpha \in \mathbb{N}^{n_1} \times \dots \times \mathbb{N}^{n_k}} \zeta^\alpha \mathbf{d}^\alpha = \sum_{\alpha \in \mathbb{N}^{n_1} \times \dots \times \mathbb{N}^{n_k}} \prod_{i=1}^k \zeta_i^{\alpha_i} \mathbf{d}_i^{\alpha_i}.$$

We recall that the dual space R^* has a natural structure of R -module [29] which is defined as follows: for all $p \in R$, and for all $\Lambda \in R^*$ consider the linear operator

$$\begin{aligned} p \star \Lambda &: R \rightarrow \mathbb{K} \\ q &\mapsto \Lambda(pq). \end{aligned}$$

In particular, we have $x_{i,j} \star \mathbf{d}_1^{\alpha_1} \dots \mathbf{d}_j^{\alpha_j} \dots \mathbf{d}_k^{\alpha_k} = \mathbf{d}_1^{\alpha_1} \dots \mathbf{d}_{j-1}^{\alpha_{j-1}} d_{1,j}^{\alpha_{1,j}} \dots d_{i-1,j}^{\alpha_{i-1,j}} d_{i,j}^{\alpha_{i,j}-1} d_{i+1,j}^{\alpha_{i+1,j}} \dots d_{n_j,j}^{\alpha_{n_j,j}} \mathbf{d}_{j+1}^{\alpha_{j+1}} \dots \mathbf{d}_k^{\alpha_k}$ if $\alpha_{i,j} > 0$ and 0 otherwise.

2.2 Tensor decomposition

In this section, we present different formulations of the tensor decomposition problem, that we consider in this paper.

We will consider hereafter a partially symmetric tensor T which is an element of $S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$ where $E_i = \langle x_{0,i}, \dots, x_{n_i,i} \rangle$. It can be represented by a partially symmetric array of coefficients

$$[T] = (T_{\alpha_1, \dots, \alpha_k})_{\alpha_i \in \mathbb{N}^{n_i+1}; |\alpha_i| = \delta_i}. \quad (1)$$

For $\alpha_i \in \mathbb{N}^{n_i}$ with $|\alpha_i| \leq \delta_i$, we denote $\bar{\alpha}_i = (\delta_i - |\alpha_i|, \alpha_{1,i}, \dots, \alpha_{n_i,i})$ and, with an abuse of notation, we identify $T_{\alpha_1, \dots, \alpha_k} := T_{\bar{\alpha}_1, \dots, \bar{\alpha}_k}$.

Such a tensor is naturally associated to a (multihomogeneous) polynomial in the variables $\mathbf{x}_1 = (x_{0,1}, \dots, x_{n_1,1}), \dots, \mathbf{x}_k = (x_{0,k}, \dots, x_{n_k,k})$

$$T(\mathbf{x}) = \sum_{\substack{\alpha = (\alpha_1, \dots, \alpha_k) \in \mathbb{N}^{n_1} \times \dots \times \mathbb{N}^{n_k}; \\ |\alpha_i| \leq \delta_i}} T_\alpha \mathbf{x}_1^{\bar{\alpha}_1} \dots \mathbf{x}_k^{\bar{\alpha}_k}.$$

or to an element $\underline{T}(\mathbf{x}) \in R_{\delta_1, \dots, \delta_k}$ obtained by substituting $x_{0,i}$ by 1 in $T(\mathbf{x})$ (for $i = 1, \dots, k$):

$$\underline{T}(\mathbf{x}) = \sum_{\substack{\alpha \in \mathbb{N}^{n_1} \times \dots \times \mathbb{N}^{n_k}; \\ |\alpha_i| \leq \delta_i}} T_\alpha \mathbf{x}_1^{\alpha_1} \dots \mathbf{x}_k^{\alpha_k}.$$

An element of $R^* = \mathbb{K}[[\mathbf{d}]]$ can also be associated naturally to T :

$$T^*(\mathbf{d}) = \sum_{\substack{\alpha \in \mathbb{N}^{n_1} \times \dots \times \mathbb{N}^{n_k}; \\ |\alpha_i| \leq \delta_i}} \binom{\delta_1}{\alpha_1}^{-1} \dots \binom{\delta_k}{\alpha_k}^{-1} T_\alpha \mathbf{d}_1^{\alpha_1} \dots \mathbf{d}_k^{\alpha_k}.$$

so that for all $T' \in R_{\delta_1, \dots, \delta_k}$,

$$\langle T(\mathbf{x}) | T'(\mathbf{x}) \rangle = T^*(\mathbf{d})(T'(\mathbf{x})).$$

The problem of decomposition of the tensor T can be stated as follows:

Tensor decomposition problem. *Given $T(\mathbf{x}) \in S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$, find a decomposition of $T(\mathbf{x})$ as a sum of products of powers of linear forms in \mathbf{x}_j :*

$$T(\mathbf{x}) = \sum_{i=1}^r \gamma_i \mathbf{l}_{1,i}(\mathbf{x}_1)^{\delta_1} \dots \mathbf{l}_{k,i}(\mathbf{x}_k)^{\delta_k} \quad (2)$$

where $\gamma_i \neq 0$, $\mathbf{l}_{j,i}(\mathbf{x}_j) = l_{0,j,i}x_{0,j} + l_{1,j,i}x_{1,j} + \dots + l_{n_j,j,i}x_{j,n_j}$ and r is the smallest possible integer for such a decomposition.

Definition 2.1 The minimal number of terms r in a decomposition of the form (2) is called the rank of T .

We say that $T(\mathbf{x})$ has an *affine decomposition* if there exists a minimal decomposition of $T(\mathbf{x})$ of the form (2) where r is the rank of T and such that $l_{0,j,i} \neq 0$ for $i = 1, \dots, r$. Notice that by a generic change of coordinates in E_i , we may assume that all $l_{0,j,i} \neq 0$ and thus that T has an affine decomposition. Suppose that $T(\mathbf{x})$ has an affine decomposition. Then by scaling $\mathbf{l}_{j,i}(\mathbf{x}_j)$ and multiplying γ_i by the inverse of the δ_j^{th} power of this scaling factor, we may assume that $l_{0,j,i} = 1$. Thus, the polynomial

$$\underline{T}(\underline{\mathbf{x}}) = \sum_{i=1}^r \gamma_i \sum_{|\alpha_i| \leq \delta_i} \binom{\delta_1}{\alpha_1} \cdots \binom{\delta_k}{\alpha_k} \zeta_{1,i}^{\alpha_1} \cdots \zeta_{k,i}^{\alpha_k} \mathbf{x}_1^{\alpha_1} \cdots \mathbf{x}_k^{\alpha_k}$$

with $T_{\alpha_1, \dots, \alpha_k} = \sum_{i=1}^r \gamma_i \sum_{|\alpha_i| \leq \delta_i} \binom{\delta_1}{\alpha_1} \cdots \binom{\delta_k}{\alpha_k} \zeta_{1,i}^{\alpha_1} \cdots \zeta_{k,i}^{\alpha_k}$. Equivalently, we have

$$T^*(\mathbf{d}) = \sum_{i=1}^r \gamma_i \sum_{|\alpha_i| \leq \delta_i} \zeta_{1,i}^{\alpha_1} \cdots \zeta_{k,i}^{\alpha_k} \mathbf{d}_1^{\alpha_1} \cdots \mathbf{d}_k^{\alpha_k}$$

so that $T^*(\mathbf{d})$ coincides on $R_{\delta_1, \dots, \delta_k}$ with the linear form

$$\sum_{i=1}^r \gamma_i \mathbf{1}_{\zeta_{1,i}, \dots, \zeta_{k,i}} = \sum_{i=1}^r \gamma_i \mathbf{1}_{\zeta_i}$$

with $\zeta_i := (\zeta_{1,i}, \dots, \zeta_{k,i}) \in \mathbb{K}^{n_1} \times \dots \times \mathbb{K}^{n_k}$.

The problem of decomposition of T can then be restated as follows:

Interpolation problem. Given $T^* \in R_{\delta_1, \dots, \delta_k}^*$ which admits an affine decomposition, find the minimal number of non-zero vectors $\zeta_1, \dots, \zeta_r \in \mathbb{K}^{n_1} \times \dots \times \mathbb{K}^{n_k}$ and non-zero scalars $\gamma_1, \dots, \gamma_r \in \mathbb{K} - \{0\}$ such that

$$T^* = \sum_{i=1}^r \gamma_i \mathbf{1}_{\zeta_i} \tag{3}$$

on $R_{\delta_1, \dots, \delta_k}$.

If such a decomposition exists, we say that $\Lambda = \sum_{i=1}^r \gamma_i \mathbf{1}_{\zeta_i} \in R^*$ extends $T^* \in R_{\delta_1, \dots, \delta_k}^*$.

2.3 Indecomposable tensors

In this section, we analyze the set of indecomposable tensor (or tensors of rank 1). They naturally form projective varieties, which we are going to describe using the language of projective geometry.

We begin by defining two auxiliary but very classical varieties, namely Segre variety and Veronese variety.

Definition 2.2 The image of the following map

$$s_k : \mathbb{P}(E_1) \times \dots \times \mathbb{P}(E_k) \rightarrow \mathbb{P}(E_1 \otimes \dots \otimes E_k) \\ (\overline{\mathbf{v}}_1, \dots, \overline{\mathbf{v}}_k) \mapsto \overline{\mathbf{v}}_1 \otimes \dots \otimes \overline{\mathbf{v}}_k$$

is the so called Segre variety of k factors. We denote it by $\Xi(E_1 \otimes \dots \otimes E_k)$.

From Definition 2.1 of the rank of a tensor and from the Interpolation Problem point of view (3) we see that a Segre variety parametrizes projective classes of rank 1 tensors $T = \mathbf{v}_1 \otimes \dots \otimes \mathbf{v}_k \in E_1 \otimes \dots \otimes E_k$ for certain $\mathbf{v}_i \in E_i$, $i = 1, \dots, k$.

Definition 2.3 Let (J_1, J_2) be a partition of the set $\{1, \dots, k\}$. If $J_1 = \{h_1, \dots, h_s\}$ and $J_2 = \{1, \dots, k\} \setminus J_1 = \{h'_1, \dots, h'_{k-s}\}$, the (J_1, J_2) -Flattening of $E_1 \otimes \dots \otimes E_k$ is the following:

$$E_{J_1} \otimes E_{J_2} = (E_{h_1} \otimes \dots \otimes E_{h_s}) \otimes (E_{h'_1} \otimes \dots \otimes E_{h'_{k-s}}).$$

Let $E_{J_1} \otimes E_{J_2}$ be any flattening of $E_1 \otimes \dots \otimes E_k$ as in Definition 2.3 and let $f_{J_1, J_2} : \mathbb{P}(E_1 \otimes \dots \otimes E_k) \rightarrow \mathbb{P}(E_{J_1} \otimes E_{J_2})$ be the obvious isomorphism. Let $[T]$ be an array associated to a tensor $T \in E_1 \otimes \dots \otimes E_k$; let $\overline{T'} = f_{J_1, J_2}(\overline{\mathbf{T}}) \in \mathbb{P}(E_{J_1} \otimes E_{J_2})$ and let $[A_{J_1, J_2}]$ be the matrix associated to T' . Then the d -minors of the matrix $[A_{J_1, J_2}]$ are said to be d -minors of $[T]$.

An array $[A] = (x_{i_1, \dots, i_k})_{0 \leq i_j \leq n_j, j=1, \dots, k}$ is said to be a generic array of indeterminates of $R = \mathbb{K}[\underline{x}_1, \dots, \underline{x}_k]$ if the entries of $[A]$ are the independent variables of R .

It is a classical result due to R. Grone (see [33]) that a set of equations for a Segre variety is given by all the 2-minors of a generic array. In [34] it is proved that, if $[A]$ is a generic array in R of size $(n_1 + 1) \times \dots \times (n_k + 1)$ and $I_d([A])$ is the ideal generated by the d -minors of $[A]$, then $I_2([A])$ is a prime ideal, therefore:

$$I(\Xi(E_1 \otimes \dots \otimes E_k)) = I_2([A]).$$

We introduce now the Veronese variety. Classically it is defined to be the d -tuple embedding of \mathbb{P}^n into $\mathbb{P}^{\binom{n+d}{d}-1}$ via the linear system associated to the sheaf $\mathcal{O}(d)$ with $d > 0$. We give here an equivalent definition.

Let E be an $n+1$ dimensional vector space. With the notation $S^d(E)$ we mean the vector subspace of $E^{\otimes d}$ of symmetric tensors.

Definition 2.4 The image of the following map

$$\begin{array}{ccc} \nu_d : \mathbb{P}(E) & \rightarrow & \mathbb{P}(S^d(E)) \\ \overline{\mathbf{v}} & \mapsto & \overline{\mathbf{v}^{\otimes d}} \end{array}$$

is the so called Veronese variety. We indicate it with $\Xi(S^d(E))$.

With this definition it is easy to see that the Veronese variety parametrizes symmetric rank 1 tensors.

Observe that if we take the vector space E to be a vector space of linear forms $\langle x_0, \dots, x_n \rangle$ then the image of the map ν_d above parametrizes homogeneous polynomials that can be written as d -th powers of linear forms.

The Veronese variety $\Xi(S^d(E)) \subset \mathbb{P}(S^d(E))$ can be also viewed as $\Xi(S^d(E)) = \Xi(E^{\otimes d}) \cap \mathbb{P}(S^d(E))$.

Let $[A] = (x_{i_1, \dots, i_d})_{0 \leq i_j \leq n, j=1, \dots, d}$ be a generic symmetric array. It is a known result that:

$$I(\Xi(S^d(E))) = I_2([A]). \quad (4)$$

See [60] for the set theoretical point of view. In [51] the author proved that $I(\Xi(S^d(E)))$ is generated by the 2-minors of a particular catalecticant matrix (for a definition of ‘‘Catalecticant matrices’’ see e.g. either [51] or [32]). A. Parolin, in his PhD thesis ([50]), proved that the ideal generated by the 2-minors of that catalecticant matrix is actually $I_2([A])$.

We are now ready to describe the geometric object that parametrizes partially symmetric tensors $T \in S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$. Let us start with the rank 1 partially symmetric tensors.

Definition 2.5 Let E_1, \dots, E_k be vector spaces of dimensions $n_1 + 1, \dots, n_k + 1$ respectively. The Segre-Veronese variety $\Xi(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ is the embedding of $\mathbb{P}(E_1) \otimes \dots \otimes \mathbb{P}(E_k)$ into $\mathbb{P}^{N-1} \simeq \mathbb{P}(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$, where $N = \left(\prod_{i=1}^k \binom{n_i + \delta_i}{\delta_i} \right)$, given by sections of the sheaf $\mathcal{O}(\delta_1, \dots, \delta_k)$. I.e. $\Xi(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ is the image of the composition of the following two maps:

$$\mathbb{P}(E_1) \times \dots \times \mathbb{P}(E_k) \xrightarrow{\nu_{\delta_1} \times \dots \times \nu_{\delta_k}} \mathbb{P}^{\binom{n_1 + \delta_1}{\delta_1} - 1} \times \dots \times \mathbb{P}^{\binom{n_k + \delta_k}{\delta_k} - 1}$$

and $\mathbb{P}^{\binom{n_1+\delta_1}{\delta_1}-1} \times \dots \times \mathbb{P}^{\binom{n_k+\delta_k}{\delta_k}-1} \xrightarrow{s} \mathbb{P}^{N-1}$, where each ν_{δ_i} is a Veronese embedding of $\mathbb{P}(E_i)$ as in Definition 2.4, then $\text{Im}(\nu_{\delta_1} \times \dots \times \nu_{\delta_k}) = \Xi(S^{\delta_1}(E_1)) \times \dots \times \Xi(S^{\delta_k}(E_k))$ and $\text{Im}(s)$ is the Segre variety of k factors. Therefore the Segre-Veronese variety is the Segre re-embedding of the product of k Veronese varieties.

If $(\delta_1, \dots, \delta_k) = (1, \dots, 1)$ then the corresponding Segre-Veronese variety is nothing else than the classical Segre variety of $\mathbb{P}(E_1 \otimes \dots \otimes E_k)$.

If $k = 1$ then the corresponding Segre-Veronese variety is nothing else than the classical Veronese variety of $\mathbb{P}(S^{\delta_1}(E_1))$.

Observe that $\Xi(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ can be viewed as the intersection with the Segre variety $\Xi(E_1^{\otimes \delta_1} \otimes \dots \otimes E_k^{\otimes \delta_k})$ that parametrizes rank one tensors and the projective subspace $\mathbb{P}(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)) \subset \mathbb{P}(E_1^{\otimes \delta_1} \otimes \dots \otimes E_k^{\otimes \delta_k})$ that parametrizes partially symmetric tensors: $\Xi(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)) = \Xi(E_1^{\otimes \delta_1} \otimes \dots \otimes E_k^{\otimes \delta_k}) \cap \mathbb{P}(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$.

In [5] it is proved that if $[A]$ is a generic array of indeterminates associated to the multihomogeneous polynomial ring $S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$ (i.e. it is a generic partially symmetric array), the ideal of the Segre-Veronese variety $\Xi(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ is

$$I(\Xi(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))) = I_2([A])$$

with $\delta_i > 0$ for $i = 1, \dots, k$.

Now if we consider the vector spaces E_i that are vector spaces of linear forms $E_i \simeq S^1(E_i)$ for $i = 1, \dots, k$, we get that the Segre-Veronese variety $\Xi(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ parametrizes multihomogeneous polynomials $F \in S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$ of the type $F = \mathbf{l}_1^{\delta_1} \dots \mathbf{l}_k^{\delta_k}$ where \mathbf{l}_i are linear forms in $S^1(E_i)$ for $i = 1, \dots, k$.

From this observation we understand that the Tensor decomposition problem of finding a minimal decomposition of type (2) for an element $T \in S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$ is equivalent to finding the minimum number of elements belonging to the Segre-Veronese variety $\Xi(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ whose span contains $\overline{T} \in \mathbb{P}(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$.

The natural geometric objects that are associated to this kind of problems are the higher secant varieties of the Segre-Veronese varieties that we are going to define.

Definition 2.6 Let $X \subset \mathbb{P}^N$ be any projective variety and define $X_s^0 := \bigcup_{\overline{\mathbf{P}}_1, \dots, \overline{\mathbf{P}}_s \in X} \langle \overline{\mathbf{P}}_1, \dots, \overline{\mathbf{P}}_s \rangle$. The s -th secant variety $X_s \subset \mathbb{P}^N$ of X is the Zariski closure of X_s^0 .

Observe that the generic element of X_s is a point $\overline{\mathbf{P}} \in \mathbb{P}^N$ that can be written as a linear combination of s points of X , in fact a generic element of X_s is an element of X_s^0 . Therefore if X is the Segre-Veronese variety, then the generic element of $\Xi_s(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ is the projective class of a partially symmetric tensor $T \in S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$ that can be written as a linear combination of s linearly independent partially symmetric tensors of rank 1. Unfortunately not all the elements of $\Xi_s(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ are of this form. In fact if $\overline{T} \in \Xi_s(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)) \setminus \Xi_s^0(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ then the rank of T is strictly bigger than s .

Definition 2.7 The minimum integer s such that $\overline{T} \in \mathbb{P}(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ belongs to $\Xi_s(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ is called the border rank of T .

In order to find the border rank of a tensor $T \in S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k)$ we should need a set of equations for $\Xi_s(S^{\delta_1}(E_1) \otimes \dots \otimes S^{\delta_k}(E_k))$ for $s > 1$. The knowledge of the generators of the ideals of secant varieties of homogeneous varieties is a very deep problem that is solved only for very particular cases (see eg. [49], [44], [41], [42], [10], [43]).

From a computational point of view, there is a very direct and well known way of getting the equations for the secant variety, which consists of introducing parameters or unknowns for the coefficients of $\mathbf{l}_{i,j}$ and γ_i in (2), to expand the polynomial and identify its coefficients with the coefficients of T . Eliminating the coefficients of $\mathbf{l}_{i,j}$ and γ_i yields the equations of the secant variety.

Unfortunately this procedure is far from being computationally practical, because we have to deal with high degree polynomials in many variables, with a lot of symmetries. This is why we need to introduce moment matrices and to use a different kind of elimination.

2.4 Moment matrices

In this section, we recall the algebraic tools and the properties we need to describe and analyze our algorithm. We refer e.g. to [8], [29], [48].

For any $\Lambda \in R^*$, we define the bilinear form Q_Λ , such that $\forall a, b \in R$, $Q(a, b) = \Lambda(ab)$. The matrix of Q_Λ in the monomial basis, of R is $\mathbb{Q}_\Lambda = (\Lambda(\mathbf{x}^{\alpha+\beta}))_{\alpha, \beta}$, where $\alpha, \beta \in \mathbb{N}^n$. Similarly, for any $\Lambda \in R^*$, we define the Hankel operator H_Λ from R to R^* as

$$H_\Lambda : R \rightarrow R^* \\ p \mapsto p \star \Lambda.$$

The matrix of the linear operator H_Λ in the monomial basis, and in the dual basis, $\{\mathbf{d}^\alpha\}$, is $\mathbb{H}_\Lambda = (\Lambda(\mathbf{x}^{\alpha+\beta}))_{\alpha, \beta}$, where $\alpha, \beta \in \mathbb{N}^n$. The following relates the Hankel operators with the bilinear forms. For all $a, b \in R$, thanks to the R -module structure, it holds

$$Q_\Lambda(a, b) = \Lambda(ab) = a \star \Lambda(b) = H_\Lambda(a)(b).$$

In what follows, we will identify H_Λ and Q_Λ .

Definition 2.8 Given $B = \{b_1, \dots, b_r\}, B' = \{b'_1, \dots, b'_{r'}\} \subset R$, we define

$$H_\Lambda^{B, B'} : \langle B \rangle \rightarrow \langle B' \rangle^*,$$

as the restriction of H_Λ to the vector space $\langle B \rangle$ and inclusion of R^* in $\langle B' \rangle^*$. Let $\mathbb{H}_\Lambda^{B, B'} = (\Lambda(b_i b'_j))_{1 \leq i \leq r, 1 \leq j \leq r'}$. If $B' = B$, we also use the notation H_Λ^B and \mathbb{H}_Λ^B .

If B, B' are linearly independent, then $\mathbb{H}_\Lambda^{B, B'}$ is the matrix of $H_\Lambda^{B, B'}$ in this basis $\{b_1, \dots, b_r\}$ of $\langle B \rangle$ and the dual basis of B' in $\langle B' \rangle^*$. The *catalecticant* matrices of [35] correspond to the case where B and B' are respectively the set of monomials of degree $\leq k$ and $\leq d - k$ ($k = 0, \dots, d$).

From the definition of the Hankel operators, we can deduce that a polynomial $p \in R$ belongs to the kernel of \mathbb{H}_Λ if and only if $p \star \Lambda = 0$, which in turn holds if and only if for all $q \in R$, $\Lambda(pq) = 0$.

Proposition 2.9 Let I_Λ be the kernel of H_Λ . Then, I_Λ is an ideal of R .

Proof. Let $p_1, p_2 \in I_\Lambda$. Then for all $q \in R$, $\Lambda((p_1 + p_2)q) = \Lambda(p_1q) + \Lambda(p_2q) = 0$. Thus, $p_1 + p_2 \in I_\Lambda$. If $p \in I_\Lambda$ and $p' \in R$, then for all $q \in R$, it holds $\Lambda(pp'q) = 0$. Thus $pp' \in I_\Lambda$ and I_Λ is an ideal. \square

Let $\mathcal{A}_\Lambda = R/I_\Lambda$ be the quotient algebra of polynomials modulo the ideal I_Λ , which, as Proposition 2.9 states is the kernel of H_Λ . The rank of H_Λ is the dimension of \mathcal{A}_Λ as a \mathbb{K} -vector space.

Definition 2.10 For any $B \subset R$, let $B^+ = B \cup x_1 B \cup \dots \cup x_n B$ and $\partial B = B^+ \setminus B$.

Proposition 2.11 Assume that $\text{rank}(H_\Lambda) = r < \infty$ and let $B = \{b_1, \dots, b_r\} \subset R$ such that \mathbb{H}_Λ^B is invertible. Then b_1, \dots, b_r is a basis of \mathcal{A}_Λ . If $1 \in \langle B \rangle$ the ideal I_Λ is generated by $\ker H_\Lambda^{B^+}$.

Proof. Let us first prove that $\{b_1, \dots, b_r\} \cap I_\Lambda = \{0\}$. Let $p \in \langle b_1, \dots, b_r \rangle \cap I_\Lambda$. Then $p = \sum_i p_i b_i$ with $p_i \in \mathbb{K}$ and $\Lambda(p b_j) = 0$. The second equation implies that $\mathbb{H}_\Lambda^B \cdot \mathbf{p} = \mathbf{0}$, where $\mathbf{p} = [p_1, \dots, p_r]^t \in \mathbb{K}^r$. Since \mathbb{H}_Λ^B is invertible, this implies that $\mathbf{p} = \mathbf{0}$ and $p = 0$.

As a consequence, we deduce that $b_1 \star \Lambda, \dots, b_r \star \Lambda$ are linearly independent elements of R^* . This is so, because otherwise there exists $\mathbf{m} = [\mu_1, \dots, \mu_r]^T \neq \mathbf{0}$, such that $\mu_1(b_1 \star \Lambda) + \dots + \mu_r(b_r \star \Lambda) = (\mu_1 b_1 + \dots + \mu_r b_r) \star \Lambda = 0$. As $\{b_1, \dots, b_r\} \cap \text{Ker}(\mathbb{H}_\Lambda) = \{0\}$, this yields a contradiction.

Consequently, $\{b_1 \star \Lambda, \dots, b_r \star \Lambda\}$ span the image of H_Λ . For any $p \in R$, it holds that $p \star \Lambda = \sum_{i=1}^r \mu_i (b_i \star \Lambda)$ for some $\mu_1, \dots, \mu_r \in \mathbb{K}$. We deduce that $p - \sum_{i=1}^r \mu_i b_i \in I_\Lambda$. This yields the decomposition $R = \langle b_1, \dots, b_r \rangle \oplus K$, $R = B \oplus I_\Lambda$, and shows that b_1, \dots, b_r is a basis of \mathcal{A}_Λ .

If $1 \in \langle B \rangle$, the ideal I_Λ is generated by the relations $x_j b_k - \sum_{i=1}^r \mu_i^{j,k} b_i \in I_\Lambda$. These are precisely in the kernel of $H_\Lambda^{B^+}$. \square

Proposition 2.12 *If $\text{rank}(H_\Lambda) = r < \infty$, then \mathcal{A}_Λ is of dimension r over \mathbb{K} and there exist $\zeta_1, \dots, \zeta_d \in \mathbb{K}^n$, where $d \leq r$, and $p_i \in \mathbb{K}[\partial_1, \dots, \partial_n]$, such that*

$$\Lambda = \sum_{i=1}^d \mathbf{1}_{\zeta_i} \circ p_i(\partial) \quad (5)$$

Moreover the multiplicity of ζ_i is the dimension of the vector space spanned the inverse system generated by $\mathbf{1}_{\zeta_i} \circ p_i(\partial)$.

Proof. Since $\text{rank}(\mathbb{H}_\Lambda) = r$, the dimension of the vector space \mathcal{A}_Λ is also r . Thus the number of zeros of the ideal I_Λ , say $\{\zeta_1, \dots, \zeta_d\}$ is at most r , viz. $d \leq r$. We can apply the structure Theorem [29, Th. 7.34, p. 185] in order to get the decomposition. \square

In characteristic 0, the inverse system of $\mathbf{1}_{\zeta_i} \circ p_i(\partial)$ by p_i is isomorphic to the vector space generated by p_i and its derivatives of any order with respect to the variables ∂_i . In general characteristic, we replace the derivatives by the product by the “inverse” of the variables [48], [29].

Definition 2.13 *For $T^* \in R_{\delta_1, \dots, \delta_k}^*$, we call generalized decomposition of T^* a decomposition such that $T^* = \sum_{i=1}^d \mathbf{1}_{\zeta_i} \circ p_i(\partial)$ where the sum for $i = 1, \dots, d$ of the dimensions of the vector spaces spanned by the inverse system generated by $\mathbf{1}_{\zeta_i} \circ p_i(\partial)$ is minimal. This minimal sum of dimensions is called the length of f .*

This definition extends the definition introduced in [35] for binary forms. The length of T^* is the rank of the corresponding Hankel operator H_Λ .

Theorem 2.14 *Let $\Lambda \in R^*$ such that $\Lambda = \sum_{i=1}^r \gamma_i \mathbf{1}_{\zeta_i}$ with $\gamma_i \neq 0$ and ζ_i distinct points of \mathbb{K}^n , iff $\text{rank } H_\Lambda = r$ and I_Λ is a radical ideal.*

Proof. If $\Lambda = \sum_{i=1}^r \gamma_i \mathbf{1}_{\zeta_i}$, with $\gamma_i \neq 0$ and ζ_i distinct points of \mathbb{K}^n . Let $\{e_1, \dots, e_r\}$ be a family of interpolation polynomials at these points: $e_i(\zeta_j) = 1$ if $i = j$ and 0 otherwise. Let I_ζ be the ideal of polynomials which vanish at ζ_1, \dots, ζ_r . It is a radical ideal. We have clearly $I_\zeta \subset I_\Lambda$. For any $p \in I_\Lambda$, and $i = 1, \dots, r$, we have $p \star \Lambda(e_i) = \Lambda(p e_i) = p(\zeta_i) = 0$, which proves that $I_\Lambda = I_\zeta$ is a radical ideal. As the quotient \mathcal{A}_Λ is generated by the interpolation polynomials e_1, \dots, e_r , H_Λ is of rank r .

Conversely, if $\text{rank } H_\Lambda = r$, by Proposition 2.12 $\Lambda = \sum_{i=1}^r \mathbf{1}_{\zeta_i} \circ p_i(\partial)$ with a polynomial of degree 0, since the multiplicity of ζ_i is 1. This concludes the proof of the equivalence. \square

In the binary case this also corresponds to the border rank of T^* , therefore the r -th minors of the Hankel operator give equations for the r -th secant variety to the rational normal curves [35].

In order to compute the zeroes of an ideal I_Λ when we know a basis of \mathcal{A}_Λ , we exploit the properties of the operators of multiplication in \mathcal{A}_Λ : $M_a : \mathcal{A}_\Lambda \rightarrow \mathcal{A}_\Lambda$, such that $\forall b \in \mathcal{A}_\Lambda, M_a(b) = ab$ and its transposed operator $M_a^t : \mathcal{A}_\Lambda^* \rightarrow \mathcal{A}_\Lambda^*$, such that for $\forall \gamma \in \mathcal{A}_\Lambda^*, M_a^T(\gamma) = a \star \gamma$.

The following proposition expresses a similar result, based on the properties of the duality.

Proposition 2.15 *For any linear form $\Lambda \in R^*$ such that $\text{rank } H_\Lambda < \infty$ and any $a \in \mathcal{A}_\Lambda$, we have*

$$H_{a \star \Lambda} = M_a^t \circ H_\Lambda \quad (6)$$

Proof. By definition, $\forall p \in R, H_{a \star \Lambda}(p) = a p \star \Lambda = a \star (p \star \Lambda) = M_a^T \circ H_\Lambda(p)$. \square

We have the following well-known theorem:

Theorem 2.16 ([25, 24, 29]) *Assume that \mathcal{A}_Λ is a finite dimensional vector space. Then $\Lambda = \sum_{i=1}^d \mathbf{1}_{\zeta_i} \circ p_i(\partial)$ for $\zeta_i \in \mathbb{K}^n$ and $p_i(\partial) \in \mathbb{K}[\partial_1, \dots, \partial_n]$ and*

- *the eigenvalues of the operators M_a and M_a^t , are given by $\{a(\zeta_1), \dots, a(\zeta_r)\}$.*
- *the common eigenvectors of the operators $(M_{x_i}^t)_{1 \leq i \leq n}$ are (up to scalar) $\mathbf{1}_{\zeta_i}$.*

Using the previous proposition, one can recover the points $\zeta_i \in \mathbb{K}^n$ by eigenvector computation as follows. Assume that $B \subset R$ with $|B| = \text{rank}(H_\Lambda)$, then equation (6) and its transposition yield

$$\mathbb{H}_{a \star \Lambda}^B = M_a^t \mathbb{H}_\Lambda^B = \mathbb{H}_\Lambda^B M_a,$$

where M_a is the matrix of multiplication by a in the basis B of \mathcal{A}_Λ . By Theorem 2.16, the common solutions of the generalized eigenvalue problem

$$(\mathbb{H}_{a \star \Lambda} - \lambda \mathbb{H}_\Lambda) \mathbf{v} = \mathbb{0} \tag{7}$$

for all $a \in R$, yield the common eigenvectors $\mathbb{H}_\Lambda^B \mathbf{v}$ of M_a^t , that is the evaluation $\mathbf{1}_{\zeta_i}$ at the roots. Therefore, these common eigenvectors $\mathbb{H}_\Lambda^B \mathbf{v}$ are up to a scalar, the vectors $[b_1(\zeta_i), \dots, b_r(\zeta_i)]$ ($i = 1, \dots, r$). Notice that it is sufficient to compute the common eigenvectors of $(\mathbb{H}_{x_i \star \Lambda}, \mathbb{H}_\Lambda)$ for $i = 1, \dots, n$

If $\Lambda = \sum_{i=1}^d \gamma_i \mathbf{1}_{\zeta_i}$ ($\gamma_i \neq 0$), then the roots are simple, and one eigenvector computation is enough: for any $a \in R$, M_a is diagonalizable and the generalized eigenvectors $\mathbb{H}_\Lambda^B \mathbf{v}$ are, up to a scalar, the evaluation $\mathbf{1}_{\zeta_i}$ at the roots.

Coming back to our problem of partially symmetric tensor decomposition, $T^* \in R_{\delta_1, \dots, \delta_k}^*$ admits an affine decomposition of rank r iff T^* coincide on $R_{\delta_1, \dots, \delta_k}$ with

$$\Lambda = \sum_{i=1}^r \gamma_i \mathbf{1}_{\zeta_i},$$

for some distinct $\zeta_1, \dots, \zeta_r \in \mathbb{K}^{n_1} \times \dots \times \mathbb{K}^{n_k}$ and some $\gamma_i \in \mathbb{K} - \{0\}$. Then, by theorem 2.14, H_Λ is of rank r and I_Λ is radical.

Conversely, given H_Λ of rank r with I_Λ radical which coincides on $R_{\delta_1, \dots, \delta_k}$ with T^* , by proposition 2.12, $\Lambda = \sum_{i=1}^r \gamma_i \mathbf{1}_{\zeta_i}$ and extends T^* , which thus admits an affine decomposition.

Therefore we can say that if the border rank of T is r then also $\text{rank}(H_\Lambda) = r$. Conversely if $\text{rank}(H_\Lambda) = r$, we can only claim that the border rank of T is at least r .

We say that $\Lambda \in R^*$ extends $T^* \in R_{\delta_1, \dots, \delta_k}^*$, if $\Lambda|_{R_{\delta_1, \dots, \delta_k}} = T^*$. The problem of decomposition of T^* can then be reformulated as follows:

Truncated moment problem. *Given $T^* \in R_{\delta_1, \dots, \delta_k}^*$, find the smallest r such that there exists $\Lambda \in R^*$ which extends T^* with H_Λ of rank r and I_Λ a radical ideal.*

In the next section, we will describe an algorithm to solve the truncated moment problem.

3 Algorithm

In this section, we first describe the algorithm from a geometric point of view and the algebraic computation it induces). Then we characterize which conditions T^* can be extended to $\Lambda \in R^*$ with H_Λ is of rank r . The algorithm is described in 3.1. It extends the one in [8] which applies only for symmetric tensors. The approach used in [6] for the rank of tensors in $\Xi_2(S^d(E))$ and in $\Xi_3(S^d(E))$ allows to avoid to loop again at step 4: if one doesn't get simple roots, then it is possible to use other techniques to compute the rank. Unfortunately the mathematical knowledge on the stratification by rank of secant varieties is nowadays not complete, hence the techniques developed in [6] cannot be used to improve algorithms for higher border ranks yet.

Algorithm 3.1: DECOMPOSITION ALGORITHM

Input: a tensor $T \in S^{\delta_1}(E_1) \otimes \cdots \otimes S^{\delta_k}(E_k)$.

Output: a minimal decomposition of T .

Set $r = 0$;

1. Determine if T^* can be extended to $\Lambda \in R^*$ with $\text{rank } H_\Lambda = r$;
 2. Find if there exists r distinct points $P_1, \dots, P_s \in \Xi(S^{\delta_1}(E_1) \otimes \cdots \otimes S^{\delta_k}(E_k))$ such that $T \in \langle P_1, \dots, P_s \rangle \simeq \mathbb{P}^{s-1}$; Equivalently compute the roots of $\ker H_\Lambda$ by generalized eigenvector computation (7) and check that the eigenspaces are simple;
 3. If the answer to 2 is YES, then it means that $T \in \Xi_r^o(S^{\delta_1}(E_1) \otimes \cdots \otimes S^{\delta_k}(E_k)) \setminus \Xi_{r-1}(S^{\delta_1}(E_1) \otimes \cdots \otimes S^{\delta_k}(E_k))$; therefore the rank of T is actually r and we are done;
 4. If the answer to 2 is NO, then it means that $T \notin \Xi_r^o(S^{\delta_1}(E_1) \otimes \cdots \otimes S^{\delta_k}(E_k))$ hence its rank is bigger than r ; Repeat this procedure from step 2 with $r + 1$.
-

We are going to characterize now under which conditions T^* can be extended to $\Lambda \in R^*$ with H_Λ of rank r (step 1).

We need the following technical property on the bases of \mathcal{A}_Λ , that we will consider:

Definition 3.1 *Let B be a subset of monomials in R . We say that B is connected to 1 if $\forall m \in B$ either $m = 1$ or there exists $i \in [1, n]$ and $m' \in B$ such that $m = x_i m'$.*

Let $B, B' \subset R_{\delta_1, \dots, \delta_k}$ be a two sets of monomials connected to 1. We consider the formal Hankel matrix

$$\mathcal{H}_\Lambda^{B, B'} = (h_{\alpha+\beta})_{\alpha \in B', \beta \in B},$$

with $h_\alpha = T^*(\mathbf{x}^\alpha) = c_\alpha$ if $\mathbf{x}^\alpha \in R_{\delta_1, \dots, \delta_k}$ and otherwise h_α is a variable. The set of these new variables is denoted \mathbf{h} .

Suppose that $\mathcal{H}_\Lambda^{B, B'}$ is invertible in $\mathbb{K}(\mathbf{h})$, then we define the formal multiplication operators

$$\mathcal{M}_{i,l}^{B, B'}(\mathbf{h}) := (\mathcal{H}_\Lambda^{B, B'})^{-1} \mathcal{H}_{x_{i,l} \star \Lambda}^{B, B'}$$

for every variable $x_{i,l} \in R$.

We use the following theorems which extend the results of [46] to the cases of distinct sets of monomials indexing the rows and columns of the Hankel operators. They characterizes the cases where $\mathbb{K}[\mathbf{x}] = B \oplus I_\Lambda$:

Theorem 3.2 *Let $B = \{\mathbf{x}^{\beta_1}, \dots, \mathbf{x}^{\beta_r}\}$ and $B' = \{\mathbf{x}^{\beta'_1}, \dots, \mathbf{x}^{\beta'_r}\}$ be two sets of monomials of in $R_{\delta_1, \dots, \delta_k}$, connected to 1 and let Λ be a linear form that belongs to $(\langle B' \cdot B^+ \rangle_{\delta_1, \dots, \delta_k})^*$. Let $\Lambda(\mathbf{h})$ be the linear form of $\langle B' \cdot B^+ \rangle^*$ defined by $\Lambda(\mathbf{h})(\mathbf{x}^\alpha) = \Lambda(\mathbf{x}^\alpha)$ if $\mathbf{x}^\alpha \in R_{\delta_1, \dots, \delta_k}$ and $h_\alpha \in \mathbb{K}$ otherwise. Then, $\Lambda(\mathbf{h})$ admits an extension $\tilde{\Lambda} \in R^*$ such that $H_{\tilde{\Lambda}}$ is of rank r with B and B' basis of $A_{\tilde{\Lambda}}$ iff*

$$\mathcal{M}_{i,l}^B(\mathbf{h}) \circ \mathcal{M}_{j,q}^B(\mathbf{h}) - \mathcal{M}_{j,q}^B(\mathbf{h}) \circ \mathcal{M}_{i,l}^B(\mathbf{h}) = 0 \quad (8)$$

($0 \leq l, q \leq k, 1 \leq i \leq n_l, 1 \leq j \leq n_q$) and $\det(\mathcal{H}_{\Lambda(\mathbf{h})}^{B', B}) \neq 0$. Moreover, such a $\tilde{\Lambda}$ is unique.

Proof. If there exists $\tilde{\Lambda} \in R^*$ which extends $\Lambda(\mathbf{h})$, with $H_{\tilde{\Lambda}}$ of rank r and B and B' basis of $A_{\tilde{\Lambda}}$ then $\mathcal{H}_{\Lambda(\mathbf{h})}^{B', B}$ is invertible and the tables of multiplications by the variables $x_{i,l}$:

$$\mathcal{M}_{i,l} := (\mathcal{H}_{\Lambda(\mathbf{h})}^{B', B})^{-1} \mathcal{H}_{x_{i,l} \star \Lambda(\mathbf{h})}^{B', B}$$

(Proposition 2.15) commute.

Conversely suppose that these matrices commute and consider them as linear operators on $\langle B \rangle$. Then by [47], we have such a decomposition $R = \langle B \rangle \oplus I$ where I is an ideal of R . As a matter of fact, using commutation relation and the fact that B is connected to 1, one can easily prove that the following morphism:

$$\begin{aligned} \pi : R &\longrightarrow \langle B \rangle \\ p &\rightarrow p(\mathcal{M})(1) \end{aligned}$$

is a projection on $\langle B \rangle$ whose kernel is an ideal I of R (note that for any $p \in \langle B \rangle$, $p(\mathcal{M})(1) = p$).

We define $\tilde{\Lambda} \in R^*$ as follows: $\forall p \in \mathbb{R}, \tilde{\Lambda}(p) = \Lambda(p(\mathcal{M})(1))$ where $p(\mathcal{M})$ is the operator obtained by substitution of the variables $x_{i,l}$ by the commuting operators $\mathcal{M}_{i,l}$. Notice that $p(\mathcal{M})$ is also the operator of multiplication by p modulo I .

Let us prove by induction on the degree of $b' \in B'$ that for all $b \in B$:

$$\Lambda(\mathbf{h})(b' b) = \Lambda(\mathbf{h})(b'(\mathcal{M})(b)) \quad (9)$$

and thus by linearity that

$$\Lambda(\mathbf{h})(b' p) = \Lambda(\mathbf{h})(b'(\mathcal{M})(p)) \quad (10)$$

for all $p \in \langle B \rangle$.

The property is obviously true for $b' = 1$. Suppose now that $b' \in B'$ is a monomial of degree strictly greater than zero. As B' is connected to 1, one has $b' = x_{j,q} b''$ for some variable $x_{j,q} \in R$ and some element $b'' \in B'$ of degree smaller than the degree of b' . By construction of the operators of multiplication ($\mathcal{M}_{i,l}$), we have

$$\Lambda(\mathbf{h})(b' b) = \Lambda(\mathbf{h})(b'' x_{j,q} b) = \Lambda(\mathbf{h})(b'' \mathcal{M}_{j,q}(b)).$$

Finally we have that $\Lambda(\mathbf{h})(b' b) = \Lambda(\mathbf{h})(b'(\mathcal{M})(b))$ and (9) is proved.

Let us deduce now that $\tilde{\Lambda}$ extends $\Lambda(\mathbf{h})$ i.e that for all $b^+ \in B^+$ and $b' \in B'$ we have:

$$\tilde{\Lambda}(b' b^+) := \Lambda(\mathbf{h})((b' b^+)(\mathcal{M})(1)) = \Lambda(\mathbf{h})(b' b^+).$$

Indeed, from (10) we have:

$$\Lambda(\mathbf{h})((b' b^+)(\mathcal{M})(1)) = \Lambda(\mathbf{h})((b'(\mathcal{M}) b^+(\mathcal{M})(1)) = \Lambda(\mathbf{h})(b' [b^+(\mathcal{M})(1)])$$

as $b^+(\mathcal{M})(1)$ belongs to $\langle B \rangle$. Then, by definition of multiplication operators ($\mathcal{M}_{i,l}$) we have

$$\Lambda(\mathbf{h})(b' [b^+(\mathcal{M})(1)]) = \Lambda(\mathbf{h})(b' b^+).$$

Thus, we have

$$\tilde{\Lambda}(b' b^+) = \Lambda(\mathbf{h})(b' b^+) \quad (11)$$

for all $b^+ \in B^+$ and $b' \in B'$ (i.e $\tilde{\Lambda}$ extends $\Lambda(\mathbf{h})$).

We eventually need to prove that $I_{\tilde{\Lambda}} = I := \text{Ker}(\pi)$. By the definition of $\tilde{\Lambda}$ we obviously have that $I \subset I_{\tilde{\Lambda}}$. Let us prove that $I_{\tilde{\Lambda}} \subset I$: assume p belongs to $I_{\tilde{\Lambda}}$, then from (11)

$$\tilde{\Lambda}(b' p(\mathcal{M})(1)) = \Lambda(\mathbf{h})(b' p(\mathcal{M})(1)) = 0$$

for all $b' \in B'$. As $p(\mathcal{M})(1) \in \langle B \rangle$ and $\det(\mathcal{H}_{\Lambda}^{B',B})(\mathbf{h}) \neq 0$, we deduce that $p(\mathcal{M})(1) = 0$ and that p belongs to I . Thus we have $I_{\tilde{\Lambda}} \subset I$.

Eventually, $\tilde{\Lambda}$ extends $\Lambda(\mathbf{h})$ with $I_{\tilde{\Lambda}} = I := \text{Ker}(\pi)$ and $\mathcal{A}_{\tilde{\Lambda}}$ equal to $R/I \simeq \langle B \rangle$ which is a zero dimensional algebra of multiplicity r with basis B .

If there exists another $\Lambda' \in R^*$ which extends $\Lambda(\mathbf{h}) \in \langle B' \cdot B^+ \rangle^*$ with $\text{rank } H_{\Lambda'} = r$, by proposition 2.11, $\ker H_{\Lambda'}$ is generated by $\ker H_{\Lambda'}^{B', B^+}$ and thus coincides with $\ker H_{\tilde{\Lambda}}$. As Λ' coincides with $\tilde{\Lambda}$ on B , the two elements of R^* must be equal. This ends the proof of the theorem. \square

The degree of these commutation relations is at most 2 in the coefficients of the multiplications matrices $\mathcal{M}_{i,l}$. A direct computation yields the following, for $m \in B$:

- If $x_{i,l}, m \in B$, and $x_{j,q} m \in B$ then $(\mathcal{M}_{i,l}^B \circ \mathcal{M}_{j,q}^B - \mathcal{M}_{j,q}^B \circ \mathcal{M}_{i,l}^B)(m) \equiv 0$ in $\mathbb{K}(\mathbf{h})$.
- If $x_{i,l} m \in B$, $x_{j,q} m \notin B$ then $(\mathcal{M}_{i,l}^B \circ \mathcal{M}_{j,q}^B - \mathcal{M}_{j,q}^B \circ \mathcal{M}_{i,l}^B)(m)$ is of degree 1 in the coefficients of $\mathcal{M}_{i,l}, \mathcal{M}_{j,q}$.
- If $x_{i,l} m \notin B$, $x_{j,q} m \notin B$ then $(\mathcal{M}_{i,l}^B \circ \mathcal{M}_{j,q}^B - \mathcal{M}_{j,q}^B \circ \mathcal{M}_{i,l}^B)(m)$ is of degree 2 in the coefficients of $\mathcal{M}_{i,l}, \mathcal{M}_{j,q}$.

We are going to give an equivalent characterization of the extension property, based on rank conditions:

Theorem 3.3 *Let $B = \{\mathbf{x}^{\beta_1}, \dots, \mathbf{x}^{\beta_r}\}$ and $B' = \{\mathbf{x}^{\beta'_1}, \dots, \mathbf{x}^{\beta'_r}\}$ be two sets of monomials in $R_{\delta_1, \dots, \delta_k}$, connected to 1. Let Λ be a linear form in $(\langle B'^+ * B^+ \rangle_{\delta_1, \dots, \delta_k})^*$ and $\Lambda(\mathbf{h})$ be the linear form of $\langle B'^+ \cdot B^+ \rangle^*$ defined by $\Lambda(\mathbf{h})(\mathbf{x}^\alpha) = \Lambda(\mathbf{x}^\alpha)$ if $\mathbf{x}^\alpha \in R_{\delta_1, \dots, \delta_k}$ and $h_\alpha \in \mathbb{K}$ otherwise. Then, $\Lambda(\mathbf{h})$ admits an extension $\tilde{\Lambda} \in R^*$ such that $H_{\tilde{\Lambda}}$ is of rank r with B and B' basis of $A_{\tilde{\Lambda}}$ iff all $(r+1) \times (r+1)$ -minors of $\mathcal{H}_{\Lambda(\mathbf{h})}^{B'^+, B^+}$ vanish and $\det(\mathcal{H}_{\Lambda(\mathbf{h})}^{B', B}) \neq 0$.*

Proof. First, if such a $\tilde{\Lambda}$ exists then $\mathcal{H}_{\Lambda(\mathbf{h})}^{B', B}$ is invertible and $H_{\tilde{\Lambda}}$ is of rank r . Thus all the $(r+1) \times (r+1)$ -minors of $\mathcal{H}_{\Lambda(\mathbf{h})}^{B'^+, B^+}$ are equal to zero.

Reciprocally, assume all $(r+1) \times (r+1)$ -minors of $\mathcal{H}_{\Lambda(\mathbf{h})}^{B'^+, B^+}$ vanish and $\det(\mathcal{H}_{\Lambda(\mathbf{h})}^{B', B}) \neq 0$ then one can consider the same operators:

$$\mathcal{M}_{i,l}^{B, B'}(\mathbf{h}) := (\mathcal{H}_{\Lambda(\mathbf{h})}^{B, B'})^{-1} \mathcal{H}_{x_{i,l} * \Lambda(\mathbf{h})}^{B, B'}.$$

By definition of these operators one has that

$$\Lambda(\mathbf{h})(x_{i,l} b b') = \Lambda(\mathbf{h})(\mathcal{M}_{i,l}(b) b') \quad (12)$$

for all $b \in B$ and $b' \in B'$. As the rank of $\mathcal{H}_{\Lambda(\mathbf{h})}^{B'^+, B^+}$ is equal to the rank of $\mathcal{H}_{\Lambda(\mathbf{h})}^{B', B}$ we easily deduce that (12) is also true for $b' \in B'^+$. Thus we have

$$\begin{aligned} \Lambda(\mathbf{h})(x_{j,q} x_{i,l} b b') &= \Lambda(\mathbf{h})(x_{i,l} b b' x_{j,q}) = \Lambda(\mathbf{h})(\mathcal{M}_{i,l}(b) b' x_{j,q}) = \\ &= \Lambda(\mathbf{h})(x_{j,q} \mathcal{M}_{i,l}(b) b') = \Lambda(\mathbf{h})([\mathcal{M}_{j,q} \mathcal{M}_{i,l}](b) b') \end{aligned}$$

for all $b \in B$, b' in B' and $x_{i,l}, x_{j,q} \in R$. Then,

$$\Lambda(\mathbf{h})([\mathcal{M}_{j,q} \mathcal{M}_{i,l}](b) b') = \Lambda(\mathbf{h})([\mathcal{M}_{i,l} \mathcal{M}_{j,q}](b) b') = \Lambda(\mathbf{h})(x_{j,q} x_{i,l} b b')$$

for all $b \in B$ and $b' \in B'$. As $\mathcal{H}_{\Lambda(\mathbf{h})}^{B', B}$ is invertible we deduce

$$[\mathcal{M}_{j,q} \mathcal{M}_{i,l}](b) = [\mathcal{M}_{i,l} \mathcal{M}_{j,q}](b)$$

for all $b \in B$. Thus

$$\mathcal{M}_{j,q} \mathcal{M}_{i,l} = \mathcal{M}_{i,l} \mathcal{M}_{j,q}.$$

Finally, we conclude the proof by using Theorem 3.2 \square

Proposition 3.4 Let $B = \{\mathbf{x}^{\beta_1}, \dots, \mathbf{x}^{\beta_r}\}$ and $B' = \{\mathbf{x}^{\beta'_1}, \dots, \mathbf{x}^{\beta'_r}\}$ be two sets of monomials of in $R_{\delta_1, \dots, \delta_k}$, connected to 1 and Λ be a linear form on $\langle B'^+ * B^+ \rangle$. Then, Λ admits an extension $\tilde{\Lambda}$ in R^* such that $H_{\tilde{\Lambda}}$ is of rank r with B (resp. B') a basis of $\mathcal{A}_{\tilde{\Lambda}}$ iff

$$\mathbb{H}^+ = \begin{pmatrix} \mathbb{H} & \mathbb{G}' \\ \mathbb{G}^t & \mathbb{J} \end{pmatrix}, \quad (13)$$

with $\mathbb{H}^+ = \mathbb{H}_{\Lambda}^{B'^+, B^+}$, $\mathbb{H} = \mathbb{H}_{\Lambda}^{B', B}$ and

$$\mathbb{G} = \mathbb{H}^t \mathbb{W}, \mathbb{G}' = \mathbb{H} \mathbb{W}', \mathbb{J} = \mathbb{W}^t \mathbb{H} \mathbb{W}'. \quad (14)$$

for some matrix $\mathbb{W} \in \mathbb{K}^{B \times \partial B}$, $\mathbb{W}' \in \mathbb{K}^{B' \times \partial B}$.

Proof. According to Theorem 3.3, $\Lambda \in \langle B'^+ * B^+ \rangle^*$ admits a (unique) extension $\tilde{\Lambda} \in R^*$ such that $H_{\tilde{\Lambda}}$ is of rank r with B (resp. B') a basis of $\mathcal{A}_{\tilde{\Lambda}}$, iff $H_{\tilde{\Lambda}}^{B'^+, B^+} = H_{\tilde{\Lambda}}^{B', B^+}$ is of rank r . Let us decompose $H_{\tilde{\Lambda}}^+$ as (13) with $\mathbb{H}^+ = \mathbb{H}_{\Lambda}^{B'^+, B^+}$, $\mathbb{H} = \mathbb{H}_{\Lambda}^{B', B}$.

If we have $\mathbb{G} = \mathbb{H}^t \mathbb{W}$, $\mathbb{G}' = \mathbb{H} \mathbb{W}'$, $\mathbb{J} = \mathbb{W}^t \mathbb{H} \mathbb{W}'$, then

$$\mathbb{H}^+ = \begin{pmatrix} \mathbb{H} & \mathbb{H} \mathbb{W}' \\ \mathbb{W}^t \mathbb{H} & \mathbb{W}^t \mathbb{H} \mathbb{W}' \end{pmatrix}$$

is clearly of rank $\leq \text{rank } \mathbb{H}$.

Conversely, suppose that $\text{rank } \mathbb{H}^+ = \text{rank } \mathbb{H}$. This implies that the image of \mathbb{G}' is in the image of \mathbb{H} . Thus, there exists $\mathbb{W}' \in \mathbb{K}^{B' \times \partial B}$ such that $\mathbb{G}' = \mathbb{H} \mathbb{W}'$. Similarly, there exists $\mathbb{W} \in \mathbb{K}^{B \times \partial B}$ such that $\mathbb{G} = \mathbb{H}^t \mathbb{W}$. Thus, the kernel of $(\mathbb{H} \ \mathbb{G}')$ (resp. $(\mathbb{H}^t \ \mathbb{G})$) contains $\begin{pmatrix} \mathbb{W}' \\ -\mathbb{I} \end{pmatrix}$ (resp. $\begin{pmatrix} \mathbb{W} \\ -\mathbb{I} \end{pmatrix}$). As $\text{rank } \mathbb{H} = \text{rank } \mathbb{H}^+ = r$, the kernel of $(\mathbb{H} \ \mathbb{G}')$ (resp. $(\mathbb{H}^t \ \mathbb{G})$) is the kernel of \mathbb{H}^+ (resp. \mathbb{H}^{+t}). Thus we have $\mathbb{J} = \mathbb{G}^t \mathbb{W}' = \mathbb{W}^t \mathbb{H} \mathbb{W}'$. \square

Notice that if \mathbb{H} is invertible, \mathbb{W}' , \mathbb{W} are uniquely determined.

Introducing new variables \mathbf{w} , \mathbf{w}' for the coefficients of the matrices \mathbb{W} , \mathbb{W}' , solving the linear system $\mathbb{G} = \mathbb{H}^t \mathbb{W}$, $\mathbb{G}' = \mathbb{H} \mathbb{W}'$, and reporting the solutions in the equation $\mathbb{J} = \mathbb{W}^t \mathbb{H} \mathbb{W}'$, we obtain a new set of equations, bilinear in \mathbf{w} , \mathbf{w}' , which characterize the existence of an extension Λ on R^* .

This leads to the following system in the variables \mathbf{h} and the coefficients \mathbf{w} of matrix \mathbb{W} . It characterizes the linear forms $\Lambda \in R_{\delta_1, \dots, \delta_k}^*$ that admit an extension $\tilde{\Lambda} \in R^*$ such that $H_{\tilde{\Lambda}}$ is of rank r with B a basis of $\mathcal{A}_{\tilde{\Lambda}}$.

$$\mathcal{H}_{\Lambda}^{B, \partial B}(\mathbf{h}) - \mathcal{H}_{\Lambda}^B(\mathbf{h}) \mathbb{W}(\mathbf{w}) = 0, \quad \mathcal{H}_{\Lambda}^{\partial B, \partial B}(\mathbf{h}) - \mathbb{W}^t(\mathbf{w}) \mathcal{H}_{\Lambda}^B(\mathbf{h}) \mathbb{W}(\mathbf{w}) = 0 \quad (15)$$

with $\det(\mathcal{H}_{\Lambda}^B(\mathbf{h})) \neq 0$.

The matrix $\mathcal{H}_{\Lambda}^{B, \partial B}$ is a quasi-Hankel matrix [48], whose structure is imposed by equality (linear) constraints on its entries. If \mathbb{H} is known (i.e. $B \times B \subset R_{\delta_1, \dots, \delta_k}$, the number of independent parameters in $\mathcal{H}_{\Lambda}^{B, \partial B}(\mathbf{h})$ or in \mathbb{W} is the number of monomials in $B \times \partial B - R_{\delta_1, \dots, \delta_k}$. By Proposition 3.4, the rank condition is equivalent to the quadratic relations $\mathbb{J} - \mathbb{W}^t \mathbb{H}^t \mathbb{W} = 0$ in these unknowns.

If \mathbb{H} is not completely known, the number of parameters in \mathbb{H} is the number of monomials in $B \times B - R_{\delta_1, \dots, \delta_k}$. The number of independent parameters in $\mathcal{H}_{\Lambda}^{B, \partial B}(\mathbf{h})$ or in \mathbb{W} is then $B \times \partial B - R_{\delta_1, \dots, \delta_k}$.

The system (15) is composed of linear equations deduced from quasi-Hankel structure, quadratic relations for the entries in $B \times \partial B$ and cubic relations for the entries in $B \times \partial B$ in the unknown parameters \mathbf{h} and \mathbf{w} .

We are going to use explicitly these characterizations in the new algorithm we propose for minimal tensor decomposition.

4 Examples and applications

There exist numerous fields in which decomposing a tensor into a sum of rank-one terms is useful. These fields range from arithmetic complexity [11] to chemistry [55]. One nice application is worth to be emphasized, namely wireless transmissions [53]: one or several signals are wished to be extracted from noisy measurements, received on an array of sensors and disturbed by interferences. The approach is deterministic, which makes the difference compared to approaches based on data statistics [20]. The array of sensors is composed of J subarrays, each containing I sensors. Subarrays do not need to be disjoint, but must be deduced from each other by a translation in space. If the transmission is narrow band and in the far field, then the measurements at time sample t recorded on sensor i of subarray j take the form:

$$T(i, j, t) = \sum_{p=1}^r A_{ip} B_{jp} C_{tp}$$

if r waves impinge on the array. Matrices A and B characterize the geometry of the array (subarray and translations), whereas matrix C contains the signals received on the array. An example with $(I, J) = (4, 4)$ is given in Figure 1. Computing the decomposition of tensor T allows to extract signals of interest as well as interferences, all included in matrix C . Radiating sources can also be localized with the help of matrix A if the exact location of sensors of a subarray are known. Note that this framework applies in radar, sonar or telecommunications.

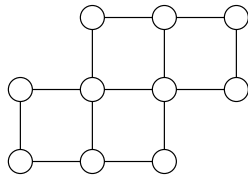


Figure 1: Array of 10 sensors decomposed into 4 subarrays of 4 sensors each.

4.1 Best approximation of lower multilinear rank

By considering a k th order tensor as a linear map from one linear space onto the tensor product of the others, one can define the i th mode rank, which is nothing else but the rank of that linear operator. Since there are k distinct possibilities to build such a linear operator, one defines a k -uplet of ranks (r_1, \dots, r_k) , called the *multilinear rank* of the k th order tensor. It is known that tensor rank is bounded below by all mode ranks r_i :

$$r \geq r_i, \forall 1 \leq i \leq k \quad (16)$$

This inequality gives us an easily accessible lower bound. Let's turn now to an upper bound.

Proposition 4.1 [3] *The rank of a tensor of order 3 and dimensions $n_1 \times n_2 \times n_3$, with $n_1 \leq n_2$, is bounded by*

$$r \leq n_1 + n_2 \lfloor n_3/2 \rfloor \quad (17)$$

This bound on maximal rank has not been proved to be always reached, and it is likely to be quite loose for large values of n_i . Nevertheless, it is sufficient for our reasoning.

There are two issues to address. First, the algorithm we have proposed is not usable in large dimensions (e.g. significantly larger than 10). The idea is then to reduce dimensions n_i down to r_i before executing the algorithm, if necessary. Second, another problem in practice is the presence of measurement errors or modeling inaccuracies, which increase the tensor rank to its generic value. We do not know how to reduce tensor rank back to its exact value. The practical solution is then to compute the best approximate of lower multilinear rank (r_1, \dots, r_k) , as explained in [21]. This best approximate always exists, and inequality (17) shows that reducing dimensions will indirectly reduce

tensor rank. To compute it, it suffices to minimize $\|T - (U^{(1)}, U^{(2)}, U^{(3)}) \cdot C\|$ with respect to the three matrices $U^{(i)}$, each of size $n_i \times r_i$, under the constraint $U^{(1)H}U^{(1)} = I$. If properly initialized by a truncated HOSVD, a few iterations of any iterative algorithm will do it [45]. The tensor of reduced dimensions is then given by $C = (U^{(1)H}, U^{(2)H}, U^{(3)H}) \cdot T$.

4.2 Number of solutions

In the above mentioned applications, it is necessary to have either a unique solution, or a finite set of solutions from which the most realistic one can be picked up. For this reason, it is convenient to make sure that the tensor rank is not too large, as pointed out by the following propositions.

Proposition 4.2 [16] *A generic symmetric tensor of order $k \geq 3$ and rank r admits a finite number of decompositions into a sum of rank one terms if $r < r_E(k, n)$, where:*

$$r_E(k, n) = \left\lceil \frac{\binom{n+k-1}{d}}{n} \right\rceil \quad (18)$$

Rank r_E is usually referred to as the expected rank of order k and dimension n .

Note that this result is true for generic tensors of rank r , which means that there exists a set of exceptions, of null measure.

This proposition has not yet been entirely extended to unconstrained tensors, which we are interested in. However, some partial results are available in the literature [1], and the following conjecture is generally admitted

Conjecture 4.3 *A generic tensor of order $k \geq 3$ and rank r admits a finite number of decompositions into a sum of rank one terms if $r < r_E(k, \mathbf{n})$, where:*

$$r_E(k, \mathbf{n}) = \left\lceil \frac{\prod_{i=1}^k n_i}{1 - k + \sum_{i=1}^k n_i} \right\rceil \quad (19)$$

where n_i denote the dimensions, $1 \leq i \leq k$

On the other hand, a sufficient condition for uniqueness has been proposed by Kruskal [38], but the bound is more restrictive:

Proposition 4.4 [38] *A tensor of order $k \geq 3$ and rank r admits a finite number of decompositions into a sum of rank one terms if:*

$$r \leq \frac{\sum_{i=1}^k \kappa_i}{2} - 1 \quad (20)$$

where κ_i denote the so-called Kruskal's ranks of loading matrices, which generically equal the dimensions n_i if the rank r is larger than the latter.

4.3 Computer results

Example If we consider a $4 \times 4 \times 7$ unconstrained tensor, it has an expected rank equal to 9, whereas Kruskal's bound generically equals 6. So it is interesting to consider a tensor with such dimensions but with rank $6 < r < 9$. In such conditions, we expect that there are almost surely a finite number of solutions, but we do not know if there is a unique one. This tensor would correspond to measurements received on the array depicted in Figure 1, if 7 time samples are recorded.

Computer results have been obtained with $4 \times 4 \times 7$ tensors of rank 7 randomly drawn according to a continuous probability distribution.

First we consider a $4 \times 4 \times 4$ tensor whose affine representation is given by:

$$T := 4 + 7a_1 + 8a_2 + 9a_3 + 5b_1 - 2b_2 + 11b_3 + 6c_1 + 8c_2 + 6c_3 + 21a_1b_1 + 28a_2b_1 + 11a_3b_1 - 14a_1b_2 - 21a_2b_2 - 10a_3b_2 + 48a_1b_3 + 65a_2b_3 + 28a_3b_3 + 26a_1c_1 + 35a_2c_1 + 14a_3c_1 + 18b_1c_1 - 10b_2c_1 + 40b_3c_1 + 36a_1c_2 + 48a_2c_2 + 18a_3c_2 + 26b_1c_2 - 9b_2c_2 + 55b_3c_2 + 38a_1c_3 + 53a_2c_3 + 14a_3c_3 + 26b_1c_3 - 16b_2c_3 + 58b_3c_3 + 68a_1b_1c_1 + 91a_2b_1c_1 + 48a_3b_1c_1 - 72a_1b_2c_1 - 105a_2b_2c_1 - 36a_3b_2c_1 + 172a_1b_3c_1 + 235a_2b_3c_1 + 112a_3b_3c_1 + 90a_1b_1c_2 + 118a_2b_1c_2 + 68a_3b_1c_2 - 85a_1b_2c_2 - 127a_2b_2c_2 - 37a_3b_2c_2 + 223a_1b_3c_2 + 301a_2b_3c_2 + 151a_3b_3c_2 + 96a_1b_1c_3 + 129a_2b_1c_3 + 72a_3b_1c_3 - 114a_1b_2c_3 - 165a_2b_2c_3 - 54a_3b_2c_3 + 250a_1b_3c_3 + 343a_2b_3c_3 + 166a_3b_3c_3.$$

If we consider $B' := (1, b_1, b_2, b_3)$ and $B := (1, a_1, a_2, a_3)$, the corresponding matrix $\mathbb{H}_\Lambda^{B', B}$ is equal to

$$\mathbb{H}_\Lambda^{B', B} = \begin{pmatrix} 4 & 7 & 8 & 9 \\ 5 & 21 & 28 & 11 \\ -2 & -14 & -21 & -10 \\ 11 & 48 & 65 & 28 \end{pmatrix}$$

and is invertible. Moreover, the transposed operators of multiplication by the variables c_1, c_2, c_3 are known:

$${}^t\mathbb{M}_{c_1}^B = \begin{pmatrix} 0 & 11/6 & -2/3 & -1/6 \\ -2 & -41/6 & 20/3 & 19/6 \\ -2 & -85/6 & 37/3 & 29/6 \\ -2 & 5/2 & 0 & 1/2 \end{pmatrix}$$

$${}^t\mathbb{M}_{c_2}^B = \begin{pmatrix} -2 & 23/3 & -13/3 & -1/3 \\ -6 & 1/3 & 7/3 & 13/3 \\ -6 & -28/3 & 29/3 & 20/3 \\ -6 & 14 & -7 & 0 \end{pmatrix}$$

$${}^t\mathbb{M}_{c_3}^B = \begin{pmatrix} 0 & 3/2 & 0 & -1/2 \\ -2 & -33/2 & 14 & 11/2 \\ -2 & -57/2 & 23 & 17/2 \\ -2 & 3/2 & 2 & -1/2 \end{pmatrix}$$

whose eigenvalues are respectively $(-1, 2, 4, 1)$, $(-2, 4, 5, 1)$ and $(-3, 2, 6, 1)$. The corresponding common eigenvectors are:

$$v_1 = \begin{pmatrix} 1 \\ -1 \\ -2 \\ 3 \end{pmatrix}, v_2 = \begin{pmatrix} 1 \\ 2 \\ 2 \\ 2 \end{pmatrix}, v_3 = \begin{pmatrix} 1 \\ 5 \\ 7 \\ 3 \end{pmatrix}, v_4 = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}.$$

We deduce that the coordinates $(a_1, a_2, a_3, b_1, b_2, b_3, c_1, c_2, c_3)$ of the 4 points of evaluation are:

$$\zeta_1 := \begin{pmatrix} -1 \\ -2 \\ 3 \\ ? \\ ? \\ ? \\ -1 \\ -2 \\ -3 \end{pmatrix}, \zeta_2 := \begin{pmatrix} 2 \\ 2 \\ 2 \\ ? \\ ? \\ ? \\ 2 \\ 4 \\ 2 \end{pmatrix}, \zeta_3 := \begin{pmatrix} 5 \\ 7 \\ 3 \\ ? \\ ? \\ ? \\ 4 \\ 5 \\ 6 \end{pmatrix}, \zeta_4 := \begin{pmatrix} 1 \\ 1 \\ 1 \\ ? \\ ? \\ ? \\ 1 \\ 1 \\ 1 \end{pmatrix},$$

Then, computing the same way the operators of multiplication ${}^t\mathbb{M}_{c_1}^{B'}$, ${}^t\mathbb{M}_{c_2}^{B'}$, ${}^t\mathbb{M}_{c_3}^{B'}$ and their common eigenvectors, we deduce:

$$\zeta_1 = \begin{pmatrix} -1 \\ -2 \\ 3 \\ -1 \\ -1 \\ -1 \\ -1 \\ -2 \\ -3 \end{pmatrix}, \zeta_2 := \begin{pmatrix} 2 \\ 2 \\ 2 \\ 2 \\ 2 \\ 3 \\ 2 \\ 4 \\ 2 \end{pmatrix}, \zeta_3 = \begin{pmatrix} 5 \\ 7 \\ 3 \\ 3 \\ -4 \\ 8 \\ 4 \\ 5 \\ 6 \end{pmatrix}, \zeta_4 = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}.$$

Finally, we have to solve the following linear system in $(\gamma_1, \gamma_2, \gamma_3, \gamma_4)$:

$$\begin{aligned} T &= \gamma_1 (1 + a_1 + a_2 + a_3) (1 + b_1 + b_2 + b_3) (1 + c_1 + c_2 + c_3) \\ &+ \gamma_2 (1 - a_1 - 2a_2 + 3a_3) (1 - b_1 - b_2 - b_3) (1 - c_1 - 2c_2 - 3c_3) \\ &+ \gamma_3 (1 + 2a_1 + 2a_2 + 2a_3) (1 + 2b_1 + 2b_2 + 3b_3) (1 + 2c_1 + 4c_2 + 2c_3) \\ &+ \gamma_4 (1 + 5a_1 + 7a_2 + 3a_3) (1 + 3b_1 - 4b_2 + 8b_3) (1 + 4c_1 + 5c_2 + 6c_3), \end{aligned}$$

We get $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 1$. We consider such an example with 6 time samples, that is an element of $\mathbb{R}^4 \otimes \mathbb{R}^4 \otimes \mathbb{R}^6$. $T := 1046 a_1 b_1 c_1 \pm 959 a_1 c_1 c_2 + 660 a_1^2 c_3 + 366 a_1 b_1 c_4 + 952 a_1 b_1 c_5 - 1318 a_1 b_2 c_1 - 1222 a_1 b_2 c_2 - 906 a_1 b_2 c_3 - 1165 a_1 b_2 c_4 - 1184 a_1 b_2 c_5 - 153 a_1 b_3 c_1 + 52 a_1 b_3 c_2 + 353 a_1 b_3 c_3 + 354 a_1 b_3 c_4 + 385 a_1 b_3 c_5 + 852 a_2 b_1 c_1 + 833 a_2 b_1 c_2 + 718 a_2 b_1 c_3 + 903 a_2 b_1 c_4 + 828 a_2 b_1 c_5 - 1068 a_2 b_2 c_1 \pm 1060 a_2 b_2 c_2 - 992 a_2 b_2 c_3 - 1224 a_2 b_2 c_4 - 1026 a_2 b_2 c_5 + 256 a_2 b_3 c_1 + 468 a_2 b_3 c_2 + 668 a_2 b_3 c_3 + 748 a_2 b_3 c_4 + 1198 a_2 b_3 c_5 - 614 a_3 b_1 c_1 - 495 a_3 b_1 c_2 - 276 a_3 b_1 c_3 - 392 a_3 b_1 c_4 - 168 a_3 b_1 c_5 + 664 a_3 b_2 c_1 + 525 a_3 b_2 c_2 + 336 a_3 b_2 c_3 + 472 a_3 b_2 c_4 + 63 a_3 b_2 c_5 + 713 a_3 b_3 c_1 + 737 a_3 b_3 c_2 + 791 a_3 b_3 c_3 + 965 a_3 b_3 c_4 + 674 a_3 b_3 c_5 - 95 a_4 b_1 + 88 a_4 b_2 + 193 a_4 b_3 + 320 a_4 c_1 + 285 a_4 c_2 + 134 a_4 c_3 + 188 a_4 c_4 + 382 a_4 c_5 - 29 a_2 b_1 - 2 a_2 b_2 + 198 a_2 b_3 + 292 a_2 c_1 + 269 a_2 c_2 + 138 a_2 c_3 + 187 a_2 c_4 + 406 a_2 c_5 + 119 a_3 b_1 - 139 a_3 b_2 + 20 a_3 b_3 - 222 a_3 c_1 - 160 a_3 c_2 + 32 a_3 c_3 + 9 a_3 c_4 - 229 a_3 c_5 + 122 b_1 c_1 + 119 b_1 c_2 + 112 b_1 c_3 + 140 b_1 c_4 + 108 b_1 c_5 - 160 b_2 c_1 - 163 b_2 c_2 - 176 b_2 c_3 - 214 b_2 c_4 - 117 b_2 c_5 + 31 b_3 c_1 + 57 b_3 c_2 + 65 b_3 c_3 + 73 b_3 c_4 + 196 b_3 c_5 - 35 a_1 - 21 a_2 + 54 a_3 - 3 b_1 - 3 b_2 + 24 b_3 + 50 c_1 + 46 c_2 + 20 c_3 + 29 c_4 + 63 c_5 - 6.$

If we take $B = \{1, a_1, a_2, a_3, b_1, b_2\}$ and $B' = \{1, c_1, c_2, c_3, c_4, c_5\}$ we obtain the following known submatrix of H_Λ :

$$\mathbb{H}_\Lambda^{B', B} = \begin{bmatrix} -6 & -35 & -21 & 54 & -3 & -3 \\ 50 & 320 & 292 & -222 & 122 & -160 \\ 46 & 285 & 269 & -160 & 119 & -163 \\ 20 & 134 & 138 & 32 & 112 & -176 \\ 29 & 188 & 187 & 9 & 140 & -214 \\ 63 & 382 & 406 & -229 & 108 & -117 \end{bmatrix}$$

which is invertible. Thus, the rank is at least 6. Let us find if H_Λ can be extended to a rank 6 Hankel matrix H_Λ . If we look at $H_\Lambda^{B'+, B^+}$, several coefficients are unknown. Yet, as will see, they can be determined by exploiting the commutation relations, as follows.

The columns $\mathbb{H}^{B', \{m\}}$ are also known for $m \in \{b_3, a_1 b_1, a_2 b_1, a_3 b_1, a_1 b_2, a_2 b_2, a_3 b_2\}$. Thus we deduce the relations between these monomials and B by solving the system

$$\mathbb{H}_\Lambda^{B', B} X = \mathbb{H}_\Lambda^{B', \{m\}}. \text{ This yields the following relations in } \mathcal{A}_\Lambda: \begin{aligned} b_3 &\equiv -1. - 0.02486 a_1 + 1.412 a_2 + 0.8530 a_3 - \\ 0.6116 b_1 + 0.3713 b_2, a_1 b_1 &\equiv -2. + 6.122 a_1 - 3.304 a_2 + .6740 a_3 + .7901 b_1 - 1.282 b_2, a_2 b_1 \equiv -2. + 4.298 a_1 - 1.546 a_2 + 1.364 a_3 + .5392 b_1 - \\ 1.655 b_2, a_3 b_1 &\equiv -2. - 3.337 a_1 + 5.143 a_2 + 1.786 a_3 - 2.291 b_1 + 1.699 b_2, a_1 b_2 \equiv -2. + 0.03867 a_1 - 0.1967 a_2 + 1.451 a_3 - 2.049 b_1 + 3.756 b_2, a_2 b_2 \equiv \\ -2. + 3.652 a_1 - 3.230 a_2 + .9425 a_3 - 2.562 b_1 + 4.198 b_2, a_3 b_2 &\equiv -2. + 6.243 a_1 - 7.808 a_2 - 1.452 a_3 + 5.980 b_1 + 0.03646 b_2 \end{aligned}$$

Using the first relation on b_3 , we can reduce $a_1 b_3, a_2 b_3, a_3 b_3$ and obtain 3 linear dependency relations between the monomials in $B \cup \{a_1^2, a_1 a_2, a_1 a_3, a_2^2, a_2 a_3, a_3^2\}$. Using the commutation relations $\frac{\text{lcm}(m_1, m_2)}{m_1} N(m_1) - \frac{\text{lcm}(m_1, m_2)}{m_2} N(m_2)$, for $(m_1, m_2) \in \{(a_1 b_1, a_2 b_1), (a_1 b_2, a_2 b_2), (a_2 b_2, a_3 b_2)\}$ where $N(m_i)$ is the reduction of m_i with respect to the prevision relations, we obtain 3 new linear dependency relations between the monomials in $B \cup \{a_1^2, a_1 a_2, a_1 a_3, a_2^2, a_2 a_3, a_3^2\}$. From these 6 relations, we deduce the expression of the monomials in $\{a_1^2, a_1 a_2, a_1 a_3, a_2^2, a_2 a_3, a_3^2\}$ as linear combinations of monomials in B :

$a_1^2 \equiv 12.08 a_1 - 5.107 a_2 + .2232 a_3 - 2.161 b_1 - 2.038 b_2 - 2.$, $a_1 a_2 \equiv 8.972 a_1 - 1.431 a_2 + 1.392 a_3 - 3.680 b_1 - 2.254 b_2 - 2.$, $a_1 a_3 \equiv -11.56 a_1 + 9.209 a_2 + 2.802 a_3 + 1.737 b_1 + .8155 b_2 - 2.$, $a_2^2 \equiv -2. + 6.691 a_1 + 2.173 a_2 + 2.793 a_3 - 5.811 b_1 - 2.846 b_2$, $a_2 a_3 \equiv -2. - 11.87 a_1 + 9.468 a_2 + 2.117 a_3 + 3.262 b_1 + 0.01989 b_2$, $a_3^2 \equiv -2. + 16.96 a_1 - 8.603 a_2 + 1.349 a_3 - 6.351 b_1 - .3558 b_2$.

Now, we are able to compute the matrix of multiplication by a_1 in B , which is obtained by reducing the monomials $B \cdot a_1 = \{a_1, a_1^2, a_1 a_2, a_1 a_3, a_1 b_1, a_1 b_2\}$ by the computed relations:

$$M_{a_1} := \begin{bmatrix} 0.0 & -2.0 & -2.0 & -2.0 & -2.0 & -2.0 \\ 1.0 & 12.08 & 8.972 & -11.56 & 6.122 & 0.03867 \\ 0.0 & -5.107 & -1.431 & 9.209 & -3.304 & -0.1967 \\ 0.0 & 0.2232 & 1.392 & 2.802 & 0.6740 & 1.451 \\ 0.0 & -2.161 & -3.680 & 1.737 & 0.7901 & -2.049 \\ 0.0 & -2.038 & -2.254 & 0.8155 & -1.282 & 3.756 \end{bmatrix}.$$

The eigenvectors of the transposed operator normalized so that the first coordinate is 1 are:

$$\begin{bmatrix} 1.0 \\ 5.0 \\ 7.003 \\ 3.0 \\ 3.0 \\ -4.0 \end{bmatrix}, \begin{bmatrix} 1.0 \\ 2.999 \\ 4.0 \\ -4.999 \\ -2.999 \\ 4.999 \end{bmatrix}, \begin{bmatrix} 1.0 \\ 2.0 \\ 2.0 \\ 2.0 \\ 2.0 \\ 2.0 \end{bmatrix}, \begin{bmatrix} 1.0 \\ 8.001 \\ 6.002 \\ -7.002 \\ 4.001 \\ -5.001 \end{bmatrix}, \begin{bmatrix} 1.0 \\ -1.0 \\ -2.0 \\ 3.0 \\ -1.0 \\ -1.0 \end{bmatrix}, \begin{bmatrix} 1.0 \\ 0.9999 \\ 0.9999 \\ 0.9999 \\ 0.9999 \\ 0.9999 \end{bmatrix}$$

They correspond to the vectors of evaluation of the monomial vector B at the roots of I_Λ . Thus we know the coordinates a_1, a_2, a_3, b_1, b_2 of these roots. By expanding the polynomial

$\gamma_1 (1 + a_1 + a_2 + a_3) (1 + b_1 + b_2 + b_3) (1 + \dots) + \gamma_2 (1 - a_1 - 2 a_2 + 3 a_3) (1 - b_1 - b_2 - b_3) (1 + \dots) + \gamma_3 (1 + 2 a_1 + 2 a_2 + 2 a_3) (1 + 2 b_1 + 2 b_2 + 3 b_3) (1 + \dots) + \gamma_4 (1 + 5 a_1 + 7 a_2 + 3 a_3) (1 + 3 b_1 - 4 b_2 + 8 b_3) (1 + \dots) + \gamma_5 (1 + 8 a_1 + 6 a_2 - 7 a_3) (1 + 4 b_1 - 5 b_2 - 3 b_3) (1 + \dots) + \gamma_6 (1 + 3 a_1 + 4 a_2 - 5 a_3) (1 - 3 b_1 + 5 b_2 + 4 b_3) (1 + \dots)$

(where the \dots are terms linear in c_i) and identifying the coefficients of T which do not depend on c_1, \dots, c_5 , we obtain a linear system in γ_i , which unique solution is $(2, -1, -2, 3, -5, -3)$. This allows us to compute the value Λ for any monomials in $\{a_1, a_2, a_3, b_1, b_2, b_3\}$. In particular, we can compute the entries of $\mathbb{H}_\Lambda^{B,B}$.

Solving the system $\mathbb{H}_\Lambda^{B,B} X = \mathbb{H}_\Lambda^{B,B'}$, we deduce the relations between the monomials in B' and B in \mathcal{A}_Λ and in particular c_1, \dots, c_5 as linear combinations of monomials in B . This allows us to recover the missing coordinates and yields the following decomposition: $T := 2(1 + a_1 + a_2 + a_3) (1 + b_1 + b_2 + b_3) (1 + c_1 + c_2 + c_3 + c_4 + c_5) - (1 - a_1 - 2 a_2 + 3 a_3) (1 - b_1 - b_2 - b_3) (1 - c_1 - 2 c_2 - 3 c_3 - 4 c_4 + 5 c_5) - 2(1 + 2 a_1 + 2 a_2 + 2 a_3) (1 + 2 b_1 + 2 b_2 + 3 b_3) (1 + 2 c_1 + 2 c_2 + 2 c_3 + 2 c_4 + 2 c_5) + 3(1 + 5 a_1 + 7 a_2 + 3 a_3) (1 + 3 b_1 - 4 b_2 + 8 b_3) (1 + 4 c_1 + 5 c_2 + 6 c_3 + 7 c_4 + 8 c_5) - 5(1 + 8 a_1 + 6 a_2 - 7 a_3) (1 + 4 b_1 - 5 b_2 - 3 b_3) (1 - 6 c_1 - 5 c_2 - 2 c_3 - 3 c_4 - 5 c_5) - 3(1 + 3 a_1 + 4 a_2 - 5 a_3) (1 - 3 b_1 + 5 b_2 + 4 b_3) (1 - 3 c_1 - 2 c_2 + 3 c_3 + 3 c_4 - 7 c_5)$.

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