Symmetry Preserving Interpolation
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We show that the so constructed symmetry adapted interpolation bases to preserve and exploit symmetry. This allows to construct bases of invariant interpolation spaces in a subspace of the polynomial ring that has a unique interpolant for each instantiated interpolation problem. We show that the unique interpolants automatically inherit the symmetry of the problem when the interpolation space is invariant (Section 3).

A canonical interpolation space, the least interpolation space, was introduced in [3–5]. We shall review that it is invariant as soon as the space of linear forms is. In floating point arithmetics though, the computed interpolation space might fail to be exactly invariant. Yet, in mathematical modeling, symmetry is often more relevant than numerical accuracy. We shall remedy this flaw and further exploit symmetry to mitigate the cost and numerical sensitivity of computing a minimal degree or least interpolation space.

As other minimal degree interpolation spaces, the least interpolation space can be constructed by Gaussian elimination in a multivariate Vandermonde (or collocation) matrix. The columns of the Vandermonde matrix are indexed by monomials. We show how any other graded basis of the polynomial ring can be used. In particular there is a two fold gain in using a symmetry adapted basis. On one hand, the computed interpolation space will be exactly invariant independently of the accuracy of the data for the interpolation problem. On the other hand, the new Vandermonde matrix is block diagonal so that Gaussian elimination can be performed independently on smaller size matrices, with better conditioning. Further computational savings result from identical blocks being repeated according to the degree of the related irreducible representations of the group. Symmetry adapted bases also played a prominent role in [2, 11, 19] where it allowed the block diagonalisation of a multivariate Hankel matrix.

In Section 2 we define minimal degree and least interpolation space and review how to compute a basis of it with Gaussian elimination. In Section 3 we make explicit how symmetry is expressed and the main ingredient to preserve it. In Section 4 we review symmetry adapted bases and show how the Vandermonde matrix becomes block diagonal in those. This is applied to provide an algorithm for the computation of invariant interpolation spaces in Section 5 together with a selection of relevant invariant and equivariant interpolation problems.

2 POLYNOMIAL INTERPOLATION

We review in this section the definitions and constructions of interpolation spaces of minimal degree. By introducing general dual polynomial bases we generalize the construction of least interpolation spaces. We shall then be in a position to work with adapted bases to preserve and exploit symmetry.
2.1 Interpolation space

Hereafter, $\mathbb{K}$ denotes either $\mathbb{C}$ or $\mathbb{R}$, $\mathbb{K}[x] = \mathbb{K}[x_1, \ldots, x_n]$ denotes the ring of polynomials in the variables $x_1, \ldots, x_n$ with coefficients in $\mathbb{K}$, $\mathbb{K}[x]_\leq \delta$ and $\mathbb{K}[x]_\delta$ the $\mathbb{K}$-vector spaces of polynomials of degree at most $\delta$ and the space of homogeneous polynomials of degree $\delta$ respectively.

The dual of $\mathbb{K}[x]$, the set of $\mathbb{K}$-linear forms on $\mathbb{K}[x]$, is denoted by $\mathbb{K}[x]^*$. A typical example of a linear form on $\mathbb{K}[x]$ is the evaluation $e_\xi$ at a point $\xi$ of $\mathbb{K}^n$. It is defined by

$$ e_\xi : \mathbb{K}[x] \rightarrow \mathbb{K} \quad \xi \mapsto \langle p, \xi \rangle. $$

Other examples of linear forms on $\mathbb{K}[x]$ are given by compositions of evaluation and differentiation

$$ \Lambda : \mathbb{K}[x] \rightarrow \mathbb{K} \quad p \mapsto \sum_{j=1}^r a_j \xi_j, \quad a_j \in \mathbb{K}. $$

Let $\xi_1, \ldots, \xi_r$ be a finite set of points in $\mathbb{K}^n$. Lagrange interpolation consists in finding, for any $n_1, \ldots, n_r \in \mathbb{K}$, a polynomial $p$ such that $e_{\xi_j}(p) = n_j, 1 \leq j \leq r$. More generally an interpolation problem is a pair $(\Lambda, \phi)$ where $\Lambda$ is a finite dimensional linear subspace of $\mathbb{K}[x]^*$ and $\phi : \Lambda \rightarrow \mathbb{K}$ is a $\mathbb{K}$-linear map. An interpolant, i.e., a solution to the interpolation problem, is a polynomial $p$ such that

$$ \phi(p) = \lambda(\Lambda) $$

(1)

An interpolation space for $\Lambda$ is a polynomial subspace $P$ of $\mathbb{K}[x]$ such that Equation (1) has a unique solution in $P$ for any map $\phi$.

2.2 Vandermonde matrix

For $P = \{p_1, p_2, \ldots, p_m\}$ and $L = \{\lambda_1, \lambda_2, \ldots, \lambda_r\}$ linearly independent sets of $\mathbb{K}[x]$ and $\mathbb{K}[x]^*$ respectively, we introduce the (generalized) Vandermonde matrix

$$ W^P_L := [\lambda_i(p_j)]_{1 \leq i \leq r, 1 \leq j \leq m}. $$

As in the univariate case, the Vandermonde matrix appears naturally in the interpolation problem. $\text{span}_x(P)$ is an interpolation space for $\text{span}_x(L)$ if and only if $W^P_L$ is an invertible matrix. This leads to a straightforward approach to compute an interpolation space for $L$. Since the elements of $L$ are linearly independent, there is $\delta > 0$ such that $W^P_{L_{\leq \delta}}$ has full row rank, where $L_{\leq \delta}$ is a basis of $\mathbb{K}[x]_{\leq \delta}$. For Lagrange interpolation $\delta = |L|$. Hence we can choose $r$ linearly independent columns $j_1, j_2, \ldots, j_r$ of $W^P_{L_{\leq \delta}}$ and the corresponding space $P = \text{span}_x(p_{j_1}, \ldots, p_{j_r})$ is an interpolation space for $\Lambda$.

In order to select $r$ linearly independent columns of $W^P_{L_{\leq \delta}}$ we can use any rank revealing decomposition of $W^P_{L_{\leq \delta}}$. Singular value decomposition (SVD) and QR decomposition provide better numerical accuracy but to obtain a minimal degree interpolation space we shall resort to Gaussian elimination. It produces a $LU$ factorization of $W^P_{L_{\leq \delta}}$ where L is an invertible matrix and $U = \{ u_{ij} \}_{1 \leq i \leq r, 1 \leq j \leq m}$ is in row echelon form. This means that there exists an increasing sequence $j_1, \ldots, j_r$ with $j_i \geq i$ such that $u_{ij_i}$ is the first non-zero entry in the $i$-th row of $U$. We call $j_1, \ldots, j_r$ the echelon index sequence of $W^P_{L_{\leq \delta}}$. They index a maximal set of linearly independent columns of $W^P_{L_{\leq \delta}}$.

2.3 Minimal degree

It is desirable to build an interpolation space such that the degree of the interpolating polynomials be as small as possible. We shall use the definition of minimal degree solution for an interpolation problem defined in [4, 5, 20].

Definition 2.1. An interpolation space $P$ for $\Lambda$ is of minimal degree if for any other interpolation space $Q$ for $\Lambda$

$$ \dim(Q \cap \mathbb{K}[x]_{\leq \delta}) \leq \dim(P \cap \mathbb{K}[x]_{\leq \delta}), \forall \delta \in \mathbb{N}. $$

We say that a countable set of homogeneous polynomials $P = \{p_1, p_2, \ldots\}$ is ordered by degree if $i \leq j$ implies that $\deg p_i \leq \deg p_j$.

Proposition 2.2. Let $L$ be a basis of $\Lambda$. Let $P_{\leq \delta}$, $\delta > 0$, be a homogeneous basis of $\mathbb{K}[x]_{\leq \delta}$ ordered by degree, such that $W^P_{L_{\leq \delta}}$ has full row rank. Let $j_1, \ldots, j_r$ be the echelon sequence of $W^P_{L_{\leq \delta}}$ obtained by Gauss elimination with partial pivoting. Then $P = \{p_{j_1}, \ldots, p_{j_r}\}$ is a minimal degree interpolation space for $\Lambda$.

Proof. Let $Q$ be another interpolation space for $\Lambda$. Let $q_1, q_2, \ldots, q_m$ be a basis of $Q \cap \mathbb{K}[x]_{\leq \delta}$ with $d \leq \delta$. Since $P_{\leq \delta}$ is a homogeneous basis of $\mathbb{K}[x]_{\leq \delta}$, any $q_i$ can be written as a linear combination of elements of $P_{\leq \delta} \cap \mathbb{K}[x]_{\leq \delta}$. Considering $q_i = \sum_{j=1}^r a_{ij} p_j$ we get that

$$ \lambda(q_i) = \sum_{j=1}^r a_{ij} \lambda(p_j) $$

for any $\lambda \in \Lambda$.

Let $\{p_{j_1}, p_{j_2}, \ldots, p_{j_m}\}$ be the elements of $P$ that form a basis of $P \cap \mathbb{K}[x]_{\leq \delta}$. Gauss elimination on $W^P_{L_{\leq \delta}}$ ensures that $\lambda(b)$ is a linear combination of $\lambda(p_{j_1}), \ldots, \lambda(p_{j_m})$ for any $b \in P_{\leq \delta} \cap \mathbb{K}[x]_{\leq \delta}$ and $\lambda \in \Lambda$. The latter implies that $\lambda(q_i) = \sum_{j=1}^m c_{ij} \lambda(p_j)$ for $1 \leq i \leq m$ and $c_{ij} \in \mathbb{K}$. If $m > n$ then the matrix $C = (c_{ij})_{1 \leq i \leq m, 1 \leq j \leq n}$ has linearly independent columns, and therefore there exist $d_1, d_2, \ldots, d_m \in \mathbb{K}$ such that $\sum_{i=1}^m d_i \lambda(q_i) = 0$ for any $\lambda \in \Lambda$ which is a contradiction with the fact that $Q$ is an interpolation space of $\Lambda$. Then we can conclude that $m \leq n$ and $P$ is a minimal degree interpolation space for $\Lambda$. □

2.4 Duality and apolar product

$\mathbb{K}[x]^*$ can be identified with the ring of formal power series $\mathbb{K}[[\theta]]$ through the isomorphism $\phi : \mathbb{K}[[\theta]] \rightarrow \mathbb{K}[x]^*$, where for $p = \sum_{\alpha \in \mathbb{N}} f_{\alpha} x^\alpha \in \mathbb{K}[x]$ and $f = \sum_{\alpha \in \mathbb{N}} f_{\alpha} \theta^\alpha \in \mathbb{K}[[\theta]]$

$$ \phi(f)(p) = \sum_{\alpha \in \mathbb{N}} f_{\alpha} \frac{\partial^\alpha p}{\partial x^\alpha}(0) = \sum_{\alpha \in \mathbb{N}} \alpha ! f_{\alpha} p_{\alpha}. $$

For instance, the evaluation $e_{\xi}$ at a point $\xi \in \mathbb{K}^n$ is represented by $e_{\xi, \alpha} = \sum_{\beta \in \mathbb{N}} (\xi, \alpha \theta^\beta)$, the power series expansion of the exponential function with frequency $\xi$. The dual pairing

$$ \langle e_{\xi}, p \rangle = \lambda(p) $$

brings the apolar product on $\mathbb{K}[x]$ by associating $p \in \mathbb{K}[x]$ to $p(\theta) \in \mathbb{K}[[\theta]]$. For $p = \sum_{\alpha} p_{\alpha} x^\alpha$ and $q = \sum_{\alpha} q_{\alpha} x^\alpha$ the apolar product between $p$ and $q$ is given by $(\langle p, q \rangle := p(\theta)q(\theta) = \sum_{\alpha} p_{\alpha} q_{\alpha}, \theta) \in \mathbb{K}$. Note that for a linear map $a : \mathbb{K}^n \rightarrow \mathbb{K}^n, \langle p, a \theta \rangle = (p \circ a^T, \theta)$. 

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For a set of linearly independent homogeneous polynomials $\mathcal{P}$ we define the dual set $\mathcal{P}^\perp$ to be a set of homogeneous polynomials such that $\langle p_i^\perp, p_j \rangle = \delta_{ij}$. For instance the dual basis of the monomial basis \( \{x^r \}_{r \in \mathbb{N}} \) is \( \{ \frac{1}{\lambda} x^r \}_{r \in \mathbb{N}} \). Thus any linear form $\lambda \in \mathbb{K}[x]^*$ can be written as $\lambda = \sum_{\alpha \in \mathbb{N}} \frac{1}{\lambda} \lambda(x^\alpha) \partial^\alpha \in \mathbb{K}[[\partial]]$. More generally, any linear form on $\mathcal{P}$ can be written as $\lambda = \sum_{p \in \mathcal{P}} \lambda(p) p^\perp(\partial)$.

### 2.5 Least interpolation space

For a space of linear forms $\Lambda \subset \mathbb{K}[x]^*$, a canonical interpolation space $\Lambda_\perp$ is introduced in [5]. It has a desirable set of properties. An algorithm to build a basis of $\Lambda_\perp$ based on Gaussian elimination on the Vandermonde matrix is presented in [4]. In this algorithm the authors consider the Vandermonde matrix associated to the monomial basis of $\mathbb{K}[x]$. The notion of dual bases introduced above, allows to extend the algorithm to any graded basis of $\mathbb{K}[x]$.

The initial term of a power series $\lambda \in \mathbb{K}[[\partial]]$, denoted by $\lambda_\perp$, $\lambda_{\perp} \in \mathbb{K}[x]$ in [3–5], is the unique homogeneous polynomial for which $\lambda - \lambda_{\perp}(\partial)$ vanishes to highest possible order at the origin. Given a linear space of linear forms $\Lambda$, we define $\Lambda_\perp$ as the linear span of all $\lambda_\perp$ with $\lambda \in \Lambda$. [5, Proposition 10] shows that $\dim \Lambda = \dim \Lambda_\perp$.

**Proposition 2.3.** Let $\mathcal{P} = \{p_1, p_2, \ldots \}$ be a homogeneous basis of $\mathbb{K}[x]$ ordered by degree and $\mathcal{L} = \{\lambda_1, \ldots, \lambda_r\}$ be a basis of $\Lambda$. Let $L = L_{\mathcal{L}}^\mathcal{P}$ be the factorization of $W_{\mathcal{L}}^\mathcal{P}$ provided by Gaussian elimination with partial pivoting with $\{l_1, l_2, \ldots, l_r\}$ as echelon index sequence. If $U = (u_{ij})$ consider, for $1 \leq \ell \leq r$,

$$h_\ell = \sum_{\deg(p_i) = \deg(p_j)} u_{\ell j} p_i^\perp$$  \hspace{1cm} (3)

where $\mathcal{P}^\perp = \{p_1^\perp, \ldots, p_r^\perp, \ldots\}$ is the dual basis of $\mathcal{P}$ with respect to the apolar product. Then $H = \{h_1, \ldots, h_r\}$ is a basis for $\Lambda_\perp$.

**Proof.** Let $L^{-1} = (a_{ij})$ and consider $c_\ell = \sum_{j \in \mathcal{L}} u_{\ell j} p_j^\perp(\partial)$. Since $u_{\ell j} = \sum_{i = 1}^r a_{i j} \lambda_i(p_j)$, then $c_\ell = \sum_{j \in \mathcal{L}} \left( \sum_{i = 1}^r a_{i j} \lambda_i(p_j) \right) p_j^\perp(\partial)$

$$= \sum_{i = 1}^r a_{i j} \sum_{j \in \mathcal{L}} \lambda_i(p_j) p_j^\perp(\partial) = \sum_{i = 1}^r a_{i j} \lambda_i \in \Lambda.$$  

Notice that $h_\ell = c_\ell \perp$ and therefore $h_\ell \in \Lambda_\perp$ for $1 \leq \ell \leq r$. The $j_i$ are strictly increasing so that $\{h_1, h_2, \ldots, h_r\}$ are linearly independent. Since $\dim(\Lambda) = \dim(\Lambda_\perp) = r$ we conclude that $H$ is a basis of $\Lambda_\perp$. \(\square\)

### 3 Symmetry

We define the concepts of invariant interpolation problem (IIP) and equivariant interpolation problem (EIP). These interpolation problems have a structure that we want to be preserved by the interpolant. We show that this is automatically achieved when choosing the interpolant in an invariant interpolation space. Then the solution of an IIP is an invariant polynomial and the solution of an EIP is an equivariant polynomial map. In Section 5 we show that the least interpolation space is invariant and how to better compute an invariant interpolation space of minimal degree.

The symmetries we shall deal with are given by the linear group action of a finite group $G$ on $\mathbb{K}^n$. It is thus given by a representation $\vartheta$ of $G$ on $\mathbb{K}^n$. It induces a representation $\rho$ of $G$ on $\mathbb{K}[x]$ given by

$$\rho(g)p(x) = p(\vartheta(g^{-1})x).$$

$\mathbb{K}[x]_\lambda$ is invariant under $\rho$. It also induces a linear representation on the space of linear forms, the dual representation of $\rho$:

$$\rho^*(\lambda)(p) = \lambda(\rho(g^{-1})p), \ p \in \mathbb{K}[x] \text{ and } \lambda \in \mathbb{K}[x]^*.$$  

We shall deal with an invariant subspace $\Lambda$ of $\mathbb{K}[x]^*$. Hence the restriction of $\rho^*$ to $\Lambda$ is a linear representation of $G$ in $\Lambda$.

### 3.1 Invariance

**Definition 3.1.** Let $\Lambda$ be a space of linear forms and $\phi : \Lambda \rightarrow \mathbb{K}$ a linear map. The pair $(\Lambda, \phi)$ defines an invariant interpolation problem if

1. $\Lambda$ is closed under the action of $G$.
2. $\phi(\rho^*(g)\lambda) = \phi(\lambda)$ for any $g \in G$ and $\lambda \in \Lambda$.

An invariant Lagrange interpolation problem can be seen as interpolation at union of orbits of points with fixed values on their orbits, i.e., given $\xi_1, \ldots, \xi_m$ with orbits $O_1, \ldots, O_m$ and $\eta_1, \ldots, \eta_m \in \mathbb{K}^n$, an interpolant $p \in \mathbb{K}[x]$ is to satisfy $p \circ \vartheta(\xi_k) = \eta_k$ for any $g \in G$. It is natural to expect that an appropriate interpolant $p$ be invariant. Yet, not all minimal degree interpolants are invariant.

**Example 3.2.** The dihedral group $D_m$ is the order of group $2m$ that leaves invariant the regular $m$-gon. It thus has a representation in $\mathbb{R}^2$ given by the matrices

$$\vartheta_k = \begin{pmatrix} \cos \left( \frac{k}{2} \frac{2\pi}{m} \right) & -\sin \left( \frac{k}{2} \frac{2\pi}{m} \right) \\ \sin \left( \frac{k}{2} \frac{2\pi}{m} \right) & \cos \left( \frac{k}{2} \frac{2\pi}{m} \right) \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \right), 0 \leq k \leq 2m-1.$$  

Consider $\Xi \subset \mathbb{R}^2$ a set of 1+3+5 points illustrated on Figure 1. They form four orbits $O_1, O_2, O_3, O_4$ of $D_5$ so that $\Lambda := \text{span}(\{\xi_k, k \in \Xi\})$ is invariant. An invariant interpolation problem is given by the pair $(\Lambda, \phi)$ where $\phi$ is defined by $\phi(\phi_k) = 0.1$ if $\xi \in O_1$, $\phi(\phi_k) = 0$ if $\xi \in O_2 \cup O_4$, and $\phi(\phi_k) = -0.5$ if $\xi \in O_3$. We show in Figure 1 the graph of the expected interpolant, but in Figure 2 we present the graph of an interpolant of minimal degree.

**Proposition 3.3.** Let $(\Lambda, \phi)$ be an invariant interpolation problem. Let $P$ be an invariant interpolation space and let $p \in \mathbb{K}[x]^G$ be the solution of $(\Lambda, \phi)$ in $P$. Then $p \in \mathbb{K}[x]^G$, the ring of invariant polynomials.

**Proof.** For any $\lambda \in \Lambda$ and $g \in G$ we have that $\lambda(p) = \phi(\lambda)$ and $\rho(g)\lambda(p) = \phi(\rho^*(g)\lambda(p))$. Since $\phi$ is $G$-invariant, we get that $\lambda(\rho(g^{-1})p) = \rho^*(g)(\lambda)(p) = \phi(\rho^*(g)\lambda) = \lambda(p)$ for any $\lambda \in \Lambda$. The latter implies that $\rho(g^{-1})p - p \in \text{Ker}\Lambda$. As $P$ is closed under the action of $\rho$, $\rho(g^{-1})p - p \in \text{Ker}\Lambda \cap P$. Then as $(\Lambda, P)$ is an interpolation space $\text{Ker}\Lambda \cap P = \{0\}$ and we conclude that $\rho(g^{-1})p - p = 0$ for any $g \in G$, i.e., $p \in \mathbb{K}[x]^G$. \(\square\)
A node per orbit

\[ \xi_1 = (0, 0) \]

\[ \xi_2 = (0.1934597, 0.1495538) \]

\[ \xi_3 = (0.4695268, 0) \]

\[ \xi_{12} = (0.6260938, 0) \]

**Figure 1:** Invariant Lagrange interpolation problem and invariant interpolon of minimal degree.

**Figure 2:** Graph of a minimal degree interpolon obtained from a monomial basis. The \( D_5 \) symmetry is not respected.

### 3.2 Equivariance

Let \( \mathbb{K}[x]^m \) be the module of polynomial mappings with \( m \) components, and let \( \theta : G \rightarrow \text{Aut}(\mathbb{K}^m) \) be a linear representation on \( \mathbb{K}^m \). A polynomial mapping \( f = (f_1, f_2, \ldots, f_m)^t \) is called \( \theta \)-equivariant if \( f(\theta(g)x) = \theta(g)f(x) \) for any \( g \in G \). The space of equivariant mappings over \( \mathbb{K} \), denoted by \( \mathbb{K}[x]^G \), is a \( \mathbb{K}[x]^G \)-module.

Equivariant maps define, for instance, dynamical systems that exhibit particularly interesting patterns and are relevant to model components, and let \( \Lambda \) be the module of polynomial mappings with \( m \) components, and let \( \theta : G \rightarrow \text{Aut}(\mathbb{K}^m) \) be a linear representation on \( \mathbb{K}^m \).

**Proposition 3.5.** Let \( \Lambda \) be an invariant interpolation problem.

**Definition 3.4.** Let \( \Lambda \) be a space of linear forms on \( \mathbb{K}[x] \) and \( \phi : \Lambda \rightarrow \mathbb{K}^m \) a linear map. The pair \( (\Lambda, \phi) \) defines an \( \theta \)-equivariant interpolation problem if

1. \( \Lambda \) is closed under the action of \( G \).
2. \( \phi(\rho^*(g^{-1})(\lambda)) = \theta(g)\phi(\lambda) \) for any \( g \in G \) and \( \lambda \in \Lambda \).

The solution of an EIP \( (\Lambda, \phi) \), is a polynomial map \( f = (f_1, \ldots, f_m)^t \) such that \( \lambda(f) = (\lambda(f_1), \ldots, \lambda(f_m))^t = \phi(\lambda) \) for any \( \lambda \in \Lambda \). It is natural to seek \( f \) as an equivariant map. It is remarkable that any type of equivariance will be respected as soon as the interpolation space is invariant.

**Proposition 3.5.** Let \( (\Lambda, \phi) \) be an equivariant interpolation problem. Let \( P \) be an invariant interpolation space for \( \Lambda \) and let \( f = (f_1, \ldots, f_m)^t \) be the solution of \( (\Lambda, \phi) \) in \( P \). Then \( f \in \mathbb{K}[x]^G \).

**Proof.** For any \( \lambda \in \Lambda \) we have the following

\[ \rho^*(g)(\lambda)f = \phi(\rho^*(g)(\lambda)) = \theta(g)\phi(\lambda) = \theta(g)\lambda(f) = \lambda(\theta(g)f). \]  

(5)

We can write \( \theta(g)f \) as \( \sum_{i=1}^{m} r_i f_i \), where \( r_i \) is a matrix representation of \( \theta(g) \). By equation (5) we get

\[ \lambda(\rho(g^{-1})f_1), \ldots, \lambda(\rho(g^{-1})f_m) = (\lambda(\sum_{i=1}^{m} r_i f_i), \ldots, \lambda(\sum_{i=1}^{m} r_i f_i)). \]

and therefore \( \rho(g^{-1})f \in \text{Ker}\Lambda \cap P = \emptyset \) for any \( 1 \leq j \leq m \) which implies that \( \lambda(\rho(g^{-1}), \ldots, f_m \lambda(\rho(g^{-1})) = \theta(g)f. \]

**Example 3.6.** The symmetry is given by the representation of the dihedral group \( D_3 \). For any \( \theta \in \Theta \), let \( \Lambda \) be a linear representation on \( \mathbb{K}^m \) such that \( \rho(\theta(g)) \in \text{Ker}\Lambda \cap P = \emptyset \) for any \( 1 \leq j \leq m \) which implies that \( \lambda(\rho(g^{-1}), \ldots, f_m \lambda(\rho(g^{-1})) = \theta(g)f. \]

**Example 3.6.** The symmetry is given by the representation of the dihedral group \( D_3 \) in Equation (4). The space \( \Lambda \) of linear forms we consider is spanned by the evaluations at the points of the orbits \( O_1 \) and \( O_2 \) of \( \xi_1 = (-\sqrt{3}, \frac{1}{2})^t \) and \( \xi_2 = (-\sqrt{3}, \frac{1}{2})^t \). We define \( \phi : \Lambda \rightarrow \mathbb{K}^2 \) by

\[ \phi(\rho(\theta(g))\xi_1) = \theta(g) \begin{pmatrix} a \\ c \end{pmatrix} \quad \text{and} \quad \phi(\rho(\theta(g))\xi_2) = \theta(g) \begin{pmatrix} b \\ d \end{pmatrix}. \]

The thus defined interpolation problem is clearly \( \theta - \theta \) equivariant. For each quadruplet \( (a, b, c, d) \in \mathbb{K}^4 \), it is desirable to find an interpolon \( (p_1, p_2)^t \in \mathbb{K}[x]^4 \) that is an \( \theta - \theta \) equivariant map. This will define the equivariant dynamical system

\[ x_1(t) = p_1(x_1(t), x_2(t)), \quad x_2(t) = p_2(x_1(t), x_2(t)) \]

whose integral curves, limit cycles and equilibrium points, will all exhibit the \( D_3 \) symmetry. In Figure 3 we draw the integral curves of equivariant vector field thus constructed. The data of the interpolation problem are illustrated by the black arrows: they are the vectors \( (a, c)^t \) and \( (b, d)^t \), with origin in the points \( \xi_1 \) and \( \xi_2 \), together with their transforms.

**Figure 3:** Integral curves for the equivariant vector field interpolating the invariant set of 12 vectors drawn in black

### 4 SYMMETRY REDUCTION

In this section we show how, when the space \( \Lambda \) of linear forms is invariant, the Vandermonde matrix can be made block diagonal. That happens when making use of symmetry adapted bases both for \( \mathbb{K}[x]^G \) and \( \Lambda \). We start by recalling their general construction, as it appears in representation theory. The material is drawn from [6, 21]. This block diagonalisation of the Vandermonde indicates how computation can be organized more efficiently, and robustly.
just draws on the invariance of the space of linear forms. So, when the evaluation points can be chosen, it makes sense to introduce symmetry among them.

### 4.1 Symmetry adapted bases

A linear representation of the group $G$ on the $\mathbb{C}$–vector space $V$ is a group morphism from $G$ to the group $GL(V)$ of isomorphisms from $V$ to itself. $V$ is called the representation space and $n$ is the dimension (or the degree) of the representation $\rho$. If $V$ has finite dimension $n$, and $\rho$ is a linear representation of $G$ on $V$, upon introducing a basis $P$ of $V$ the isomorphism $\rho(g)$ can be described by a non-singular $n \times n$ matrix. This representing matrix is denoted by $[\rho(g)]_P$. The complex-value function $\chi : G \to \mathbb{C}$, with $\chi(g) \to \text{Trace}(\rho(g))$ is the character of the representation $\rho$.

The dual or contragredient representation of $\rho$ is the representation $\rho^*$ on the dual vector space $V^*$ defined by:

$$\rho^*(g)(\lambda) = \lambda \circ \rho(g^{-1}) \text{ for any } \lambda \in V^*. \hspace{1cm} (6)$$

If $P$ is a basis of $V$ and $P^*$ its dual basis then $[\rho^*(g)]_{P^*} = [\rho(g)^{-1}]_P^t$.

It follows that $\chi^*(g) = \chi(g)\chi(g)^{-1} = \chi(g)^{-1}$.

A linear representation $\rho$ of a group $G$ on a space $V$ is irreducible if there is no proper subspace $W$ of $V$ with the property that, for every $g \in G$, the isomorphism $\rho(g)$ maps every vector of $W$ into $W$. In this case, its representation space $V$ is also called irreducible. The contragredient representation $\rho^*$ is irreducible when $\rho$ is. A finite group has a finite number of inequivalent irreducible representations. Any representation of a finite group is completely reducible, meaning that it decomposes into a finite number of irreducible subspaces.

Let $\rho_j (j = 1, \ldots, N)$ be the irreducible $n_j$ dimensional representations of $G$. The complete reduction of the representation $\rho$ and its representation space are denoted by $\rho = c_1 \rho_1 \oplus \cdots \oplus c_N \rho_N$ and $V = V_1 \oplus \cdots \oplus V_N$. Each invariant subspace $V_j$ is the direct sum of $c_j$ irreducible subspaces and the restriction of $\rho$ to each one is equivalent to $\rho_j$. The $(c_j n_j)$-dimensional subspaces $V_j$ of $V$ are the isotypic components. With $\chi_j$ the character of $\rho_j$ we determine the multiplicity $c_j$ and the projection $\pi_j$ onto the isotypic component $V_j$:

$$c_j = \frac{1}{|G|} \sum_{g \in G} \chi_j(g) \chi(g). \hspace{1cm} (7)$$

To go further in the decomposition, consider the representing matrices $R_j(g) = \left( r_{a \beta}^j(g) \right)_{1 \leq a, \beta \leq n_j}$ for $\rho_j$. For $1 \leq a, \beta \leq n_j$, let

$$\pi_{j, \alpha \beta} = \frac{n_j}{|G|} \sum_{g \in G} r_{a \alpha}^j(g^{-1}) r_{\beta \beta}(g). \hspace{1cm} (8)$$

Let $\{p_{i_1}^j, \ldots, p_{i_{n_j}}^j\}$ be a basis of the subspace $V_{j,1} = \pi_{j,1,11}(V_j)$. A symmetry adapted basis of the isotypic component $V_j$ is then given by

$$P_j = \{p_{i_1}^j, \ldots, p_{i_{n_j}}^j, \pi_{j,1,11}(p_{i_1}^j), \ldots, \pi_{j,1,11}(p_{i_{n_j}}^j)\}. \hspace{1cm} (9)$$

The union $\bigcup_j P_j$ of $V_j$ is a symmetry adapted basis for $V$.

Indeed, by [21, Proposition 8], the set $\{\pi_{j,1,11}(p_{i_1}^j), \ldots, \pi_{j,1,11}(p_{i_{n_j}}^j)\}$ is a basis of $V_{j,1} = \pi_{j,1,11}(V_j)$ and $V_j = V_{j,1} \oplus \cdots \oplus V_{j,n_j}$. Furthermore $\{p_{i_1}^j, \pi_{j,21}(p_{i_1}^j), \ldots, \pi_{j,1,11}(p_{i_{n_j}}^j)\}$ is a basis of an irreducible space with representing matrices $\left( r_{a \alpha}^j(g) \right)_{1 \leq a, \beta \leq n_j}$. Hereafter we denote by $\mathcal{P}^{\rho,\alpha}_{j}$ the polynomial map defined by

$$\mathcal{P}^{\rho,\alpha}_{j} = \left( \pi_{j,1,11}(p_{i_1}^j), \ldots, \pi_{j,1,11}(p_{i_{n_j}}^j) \right). \hspace{1cm} (10)$$

A symmetry adapted basis $P$ is characterized by the fact that $[\rho(g)]_P = \text{diag}(R_1(g) \otimes 1_{c_1}, \ldots, R_N(g) \otimes 1_{c_N})$. Then $[\rho^*(g)]_{P^*} = \text{diag}(R_1(g^{-1}) \otimes 1_{c_1}, \ldots, R_N(g^{-1}) \otimes 1_{c_N}) \mid 1 = 1, \ldots, N \}$.

**Proposition 4.1.** If $P = \bigcup_{j=1}^N P_j$ be a symmetry adapted basis of $V$ where $P_j$ spans the isotypic component associated to $\rho_j$ then its dual basis $P^* = \bigcup_{j=1}^N P^*_j$ in $V^*$ is a symmetry adapted basis where $P^*_j$ spans the isotypic component associated to $\rho_j^*$.

**Corollary 4.2.** If $P$ is a symmetry adapted basis of $\mathbb{K}[x]_{\leq \delta}$, so is its dual $P^*$ with respect to the apolar product.

A scalar product is $G$–invariant with respect to a linear representation $\rho$ if $\langle v, w \rangle = \langle \rho(g)(v), \rho(g)(w) \rangle$ for any $g \in G$ and $v, w \in V$. If we consider unitary representing matrices $R_j(g)$, and an orthonormal basis $\{p_1^j, \ldots, p_{n_j}^j\}$ of $V_j$, with respect to a $G$–invariant inner product, then the same process leads to an orthornormal symmetry adapted basis [6, Theorem 5.4].

Some irreducible representations might not have representing matrices in $\mathbb{R}$. Yet one can determine a real symmetry adapted basis [2] by combining the isotypic components related to conjugate irreducible representations. This happens for instance for abelian groups and we shall avoid them in the examples of this paper for lack of space. Indeed the completely general statements become convoluted when working with the distinction.

### 4.2 Block diagonal Vandermonde matrix

We consider a linear representation $\theta$ of a finite group $G$ on $\mathbb{K}^n$. It induces the representations $\rho$ and its dual $\rho^*$ on the space $\mathbb{K}[x]$ and $\mathbb{K}[x]_\delta$. $\mathbb{K}[x]_\delta$ is invariant under $\rho$ and thus can be decomposed into isotypic components $\mathbb{K}[x]_\delta = \bigoplus_{j=1}^N P_j$, where $P_j$ is associated to the irreducible representation $\rho_j$ of $G$, with character $\chi_j$. Each $P_j$ is the image of $\mathbb{K}[x]_\delta$ under the map $\pi_j$, as defined in (7).

For an invariant subspace $\Lambda$ of $\mathbb{K}[x]$ the restriction of $\rho^*$ to $\Lambda$ is a linear representation of $G$. We shall arrange the isotypic decomposition $\Lambda = \Lambda_1 \oplus \cdots \oplus \Lambda_N$ such that $\Lambda_j$ is the isotypic component associated to the irreducible representation $\rho_j^*$, with character $\overline{\chi_j}$. To make a distinction we denote $\pi_{j,a}^\Lambda$ as the map defined in (8) associated to $\rho_j^*$.

**Proposition 4.3.** Let $\rho$ and $\rho^*$ be linear representations of a finite group $G$ on $\mathbb{K}[x]_{\leq \delta}$ and $\Lambda$ defined as above. Let $P = \bigcup_{j=1}^N P_j^j$ be a symmetry adapted basis of $\mathbb{K}[x]_{\leq \delta}$ with

- $\{p_1^j, \ldots, p_{n_j}^j\}$ a basis of $\pi_{j,1,11}(\mathbb{K}[x]_{\leq \delta})$.
- $P_j^j = \{p_1^j, \ldots, p_{n_j}^j, \pi_{j,1,11}(p_1^j), \ldots, \pi_{j,1,11}(p_{n_j}^j)\}$.

Let $\mathcal{L} = \bigcup_{j=1}^N \mathcal{L}_j$ be a symmetry adapted basis of $\Lambda$ with

- $\{\lambda_1^j, \ldots, \lambda_{n_j}^j\}$ a basis of $\pi_{j,1,11}(\Lambda)$.
- $\mathcal{L}_j = \{\lambda_1^j, \ldots, \lambda_{n_j}^j, \pi_{j,1,11}(\lambda_1^j), \ldots, \pi_{j,1,11}(\lambda_{n_j}^j)\}$.
Then the Vandermonde matrix $W^p_L$ is given by
\[
\text{diag}\left(\lambda_i, \lambda_{j\alpha}\right)_{1 \leq i, j \leq r}, \quad i = 1 \ldots N\right),
\]
where $\otimes$ denotes the Kronecker product.

Proof. Let $\alpha, \beta, \gamma, \sigma, \pi \in \mathbb{N}$ such that $1 \leq \alpha, \beta \leq n_1$ and $1 \leq \gamma, \sigma \leq n_i$. Let $\lambda_{i\alpha\beta} = \pi_i \gamma_1 \alpha_1 \beta_1$ and $p^\rho_{i\gamma_1 \alpha_1 \beta_1} = \gamma_{i\gamma_1 \alpha_1 \beta_1}$ for any entry $\lambda_{i\alpha\beta}(p^\rho_{i\gamma_1 \alpha_1 \beta_1})$ in $W^p_L$ we have the following:
\[
\lambda_{i\alpha\beta}(p^\rho_{i\gamma_1 \alpha_1 \beta_1}) = \lambda_{i\alpha\beta}(\pi_i \gamma_1 \alpha_1 \beta_1) = \lambda_{i\alpha\beta}\left(\frac{n_1}{|G|} \sum_{g \in G} r^\rho_i \gamma_1 \alpha_1 \beta_1(g) \rho(g) \right) = \frac{n_1}{|G|} \sum_{g \in G} r^\rho_i \gamma_1 \alpha_1 \beta_1(g) \rho(g) \lambda_{i\alpha\beta}(p^\rho_{i\gamma_1 \alpha_1 \beta_1}).
\]

Using Proposition [21, Proposition 8] (2) if $i \neq j$, $\pi_i \gamma_1 \alpha_1 \beta_1(p^\rho_{i\gamma_1 \alpha_1 \beta_1}) = 0$ then $\lambda_{i\alpha\beta}(p^\rho_{i\gamma_1 \alpha_1 \beta_1})$ is zero for $i \neq j$, i.e., $W^p_L$ is block diagonal in the isotypic components. Now if $i = j$
\[
\lambda_{i\alpha\beta}(p^\rho_{i\gamma_1 \alpha_1 \beta_1}) = \pi_i \gamma_1 \alpha_1 \beta_1(p^\rho_{i\gamma_1 \alpha_1 \beta_1}) = \pi_i \gamma_1 \alpha_1 \beta_1\lambda_{i\alpha\beta}(p^\rho_{i\gamma_1 \alpha_1 \beta_1}).
\]

Since $\pi_i \gamma_1 \alpha_1 \beta_1 \lambda_{i\alpha\beta}(p^\rho_{i\gamma_1 \alpha_1 \beta_1})$ if $i = j$ and $a = \gamma$, using the fact that $\pi_i \gamma_1 \alpha_1 \beta_1 = \lambda_{i\alpha\beta}$ we get that
\[
\lambda_{i\alpha\beta}(p^\rho_{i\gamma_1 \alpha_1 \beta_1}) = \left\{ \begin{array}{ll} \lambda_{i\alpha\beta}(p^\rho_{i\gamma_1 \alpha_1 \beta_1}) & \text{if } i = j \\ 0 & \text{otherwise} \end{array} \right. (11)
\]

Thus the Vandermonde matrix $W^p_L$ has the announced block diagonal structure.

\[
\text{Remark 1. At the heart of the above proof is the following property: for a representation } \chi = \bigoplus_{j=1}^N V_j \text{ of } G, \text{ and its dual } \chi^* = \bigoplus_{j=1}^{|N|} V^*_j, \text{ we have } \lambda(\chi) = 0 \text{ as soon as } \lambda \in \chi^*_i \text{ while } \nu \in \chi^* \text{ for } i \neq j.
\]

\[
\text{Example 4.4. Let } G = \text{ the dihedral group } D_3 \text{ of order } 6. \text{ A representation of } G \text{ on } \mathbb{R}^2 \text{ is given by Equation (4) with } m = 3. D_3 \text{ has three irreducible representations, two of dimension 1 and one of dimension 2.}
\]

Consider $\Xi$ the orbit of the point $\xi = \left(-\frac{\sqrt{3}}{3}, \frac{\sqrt{3}}{3} \right)^T$ in $\mathbb{R}^2$, with $\xi = \delta_i - \xi_1$. Let $\Lambda = \text{span}(e^{\xi}, \Delta^{\xi}_1)$ with $\Delta^{\xi}_1$ the directional derivative with direction $\xi$. $\Lambda$ is closed under the action of $G$. Indeed for any $p \in \mathbb{R}[x, y]$, $\rho_i(p) = \gamma_{i\gamma_1 \alpha_1 \beta_1}(p) = \gamma_{i\gamma_1 \alpha_1 \beta_1}(\delta^{\xi}_1 + \gamma_{i\gamma_1 \alpha_1 \beta_1}(\delta^{\xi}_1)) = \delta^{\xi}_1 \gamma_{i\gamma_1 \alpha_1 \beta_1}(p)$. Considering $\gamma_{i\gamma_1 \alpha_1 \beta_1}(p)$ for some $1 \leq j \leq 6$ we have $p^{\rho_i}(\xi_1, \Delta^{\xi}_1) = \gamma_{i\gamma_1 \alpha_1 \beta_1}(\delta^{\xi}_1)$, a symmetry adapted basis of $A$ is given by
\[
\mathcal{L} := \begin{bmatrix} \{1, 0, 0\} & \{1, 0, 0\} & \{1, 0, 0\} \\ \{0, 1, 0\} & \{0, 1, 0\} & \{0, 1, 0\} \\ \{0, 0, 1\} & \{0, 0, 1\} & \{0, 0, 1\} \end{bmatrix},
\]
with $A = \mathbb{R}_3$, $A = \mathbb{R}_3$, $A = \mathbb{R}_3$, $A = \mathbb{R}_3$, $A = \mathbb{R}_3$, $A = \mathbb{R}_3$. A symmetry adapted basis of $\mathbb{R}[x] \leq 3$ is given by
\[
P^\rho := \begin{bmatrix} 1, x_1, x_1^2, \quad x_1^3, \quad x_2, \quad x_2^3, \quad x_1x_2, \quad x_1^2x_2, \quad x_1x_2^2 \end{bmatrix}
\]

The Vandermonde matrix $W^p_L$ is block diagonal:
\[
W^p_L = \begin{bmatrix} A_1 & 0 & 0 \\ 0 & A_2 & 0 \\ 0 & 0 & A_3 \end{bmatrix}, \quad A_1 = \begin{bmatrix} \frac{1}{2} & -3 & 4 \\ -3 & \frac{1}{2} & -4 \end{bmatrix}, \quad A_2 = \begin{bmatrix} \frac{1}{4} & -1 & -\frac{1}{2} \\ -1 & \frac{1}{4} & -\frac{1}{2} \end{bmatrix}, \quad A_3 = \begin{bmatrix} 1 & 2 & 3 \\ 2 & 1 & 3 \end{bmatrix}
\]

5 EQUIVARIANT INTERPOLATION

In this section we shall first show how to build interpolation spaces of minimal degree that are invariant. We shall actually build symmetry adapted bases for these, exploiting the block diagonal structure of the Vandermonde matrix. Doing so we prove that the least interpolation space is invariant. We then present a selection of invariant or equivariant interpolation problems. As proved in Section 3, the invariance or equivariance is preserved by the interpolant when the interpolation space is invariant. The use of the symmetry adapted bases constructed allows this equivariance to be preserved exactly, independently of the numerical accuracy.

5.1 Constructing invariant interpolation spaces

The starting point is a representation $\chi$ of $G$ on $\mathbb{R}^n$ that induces representations $\rho$ and $\rho^*$ on $\mathbb{R}[x]$ and $\mathbb{R}[x]^*$. It is no loss of generality to assume that $\chi$ is an orthogonal representation. The apolar product is thus $G$-invariant.

Let $A$ be an invariant subspace of $\mathbb{R}[x]^*$. Hereafter $A$ is a symmetry adapted basis of $A$ and $\mathcal{P}$ a symmetry adapted basis of $\mathbb{R}[x]_{\leq 8}$ consisting of homogeneous polynomials. The elements of $\mathcal{P}$ corresponding to the same irreducible component are ordered by degree.

According to Proposition 4.3, $W^p_L = \text{diag}(I_{n_1} \otimes A_i)$. In the factorization $L \cup_1 U_i := A_i$ provided by Gauss elimination, let $j_1, j_2, \ldots, j_r$ be the echelon index sequence of $U_i$; $r_i$ is the multiplicity of $p^i_{j_1}$ in $A$. An echelon index sequence for $D_3 = I_{n_1} \otimes A_i$ is given by
\[
S_i = \sum_{k=0}^{c_i-1} (j_1 + kn_1, j_2 + kn_1, \ldots, j_r + kn_1).
\]

An echelon index sequence of $W^p_L$ is given by $S = \bigcup_{i=1}^N S_i$. Let $P^i_{\Lambda}$ be the set of elements of $\mathcal{P}$ that are indexed by elements of $S_i$. From (9) we get that
\[
P^i_{\Lambda} = \{b^i_{j_1}, \ldots, b^i_{j_r}, \ldots, \pi_{i,n_1}(b^i_{j_1}), \ldots, \pi_{i,n_1}(b^i_{j_r}) \}
\]

We prove the assertions made on the outputs of the algorithm.

Proposition 5.1. The set of polynomials $P^i_{\Lambda}$ built it in Algorithm 1 spans a minimal degree interpolation space for $A$ that is invariant under the action of $\rho$. $P^i_{\Lambda}$ is furthermore a symmetry adapted basis for this space.

6
Algorithm 1 Invariant interpolation space

\textbf{In:} \( \mathcal{P} \) and \( S \) a.s.b of \( \mathbb{K}[x] \) and \( \Lambda \) respectively.

\textbf{Out:} a.s.b \( \mathcal{P}_\Lambda \) of an invariant interpolation space of min. degree
- a symmetry adapted basis \( \mathcal{H}_\Lambda \) of \( \Lambda \).

1. Compute \( W^P_L \);
2. for \( i = 1 \) to \( N \) do
3. \( A_i := L_i U_i \); with \( U_i = \left( \frac{u(j)}{\ell_k} \right)_{\ell_k} \) \( \triangleright \) LU factorization of \( A_i \)
4. \( J := (j_1, \ldots, j_r) \);
5. echelon index sequence of \( U_i \)
6. \( \mathcal{P}_\Lambda \leftarrow \{ p \in \mathcal{P}^i \) and \( \ell \in S_i \} \);
7. \( \mathcal{H}_\Lambda := \left\{ \sum_{d=0}^{n_i} \mathcal{H}_\Lambda \left( \sum_{d=0}^{n_i} \mathcal{H}_\Lambda \right) \right\} \)
8. return \( \mathcal{P}_\Lambda, \mathcal{H}_\Lambda \);

Proof. Since the elements of \( \mathcal{P}_\Lambda \) are indexed by the elements of \( S \) then \( W^P_L \) is invertible and therefore \( \mathcal{P}_\Lambda \) is an interpolation space for \( \Lambda \). The elements of \( \mathcal{P}_\Lambda \) correspond to the same blocks of \( W^P_L \) are ordered by degree. Then as a direct consequence of Proposition 2.2, \( \mathcal{P}_\Lambda \) is a minimal degree interpolation space. Let \( \pi \) be a symmetry built it in Algorithm 1 is a symmetry adapted basis for \( \Lambda \).

\textbf{Proposition 5.2.} The set \( \mathcal{H}_\Lambda \) built it in Algorithm 1 is a symmetry adapted basis for \( \Lambda \).

Proof. By Proposition 2.3 we get that \( \mathcal{H}_\Lambda \) is a basis of \( \Lambda \). Let \( \mathcal{H}_\Lambda := \{ h_{\ell, a} \} \subset \mathcal{V}^a \cap \mathcal{H}_\Lambda \) with \( 1 \leq a \leq c_j \). By the block diagonal structure and Corollary 4.2 we have

\[ h_{\ell, a} = \sum_k u_k^{(j)} \pi_{\ell, a} \left( q_k \right) = \pi_{\ell, a} \left( \sum_k u_k^{(j)} q_k \right) = \pi_{\ell, a} \left( h_{\ell, 1} \right). \]

Therefore \( \mathcal{H}_\Lambda \) has the following structure

\[ \mathcal{H}_\Lambda := \{ h_{\ell, a} \} \subset \mathcal{V}^a \cap \mathcal{H}_\Lambda \]

Since for any \( \ell, a \), \( \pi_{\ell, a} \) form a basis of an irreducible representation of \( \Lambda \) we can conclude that \( \mathcal{H}_\Lambda \) is a symmetry adapted basis of \( \Lambda \).

As pointed out in Section 4.1, we can construct a symmetry adapted basis \( \mathcal{P} \) of \( \mathbb{K}[x] \) that is orthonormal with respect to the apolar product. Then \( \mathcal{P} = \mathcal{P}^L \) and the basis \( \mathcal{P}_\Lambda \) built in Algorithm 1 is orthonormal. Moreover if in the third step of Algorithm 1 we use Gauss Elimination by segment as in [4], then \( \mathcal{H}_\Lambda \) is an orthonormal symmetry adapted basis of \( \Lambda \).

With this construction we repoved that \( \Lambda \) is invariant. The above approach to computing a basis of \( \Lambda \) is advantageous in two ways. First Gaussian elimination is performed only on smaller blocks. But also, when solving invariant and equivariant interpolation problems, the result will respect exactly the intended invariance or equivariance, despite possible numerical inaccuracy.

5.2 Computing interpolants

We consider an interpolation problem \( (\Lambda, \phi) \) where \( \Lambda \) is a \( G \)-invariant subspace of \( \mathbb{K}[x] \) and \( \phi : \Lambda \to \mathbb{K}^m \). Take \( \mathcal{P} \) to be a symmetry adapted basis of an invariant interpolation space \( P \) for \( \Lambda \) as obtained from Algorithm 1. The interpolant polynomial \( p \) that solves \( (\Lambda, \phi) \) in \( P \) is given by

\[ p = \sum_{i=1}^{N} \sum_{a=1}^{n_x} A_{i}^{-1} \phi(L_i, a)^{t}(p_i, \alpha)^{t}, \quad (12) \]

where \( \phi(L_i, a)^{t} \) and \( A_{i}^{-1} \) are as in (10) and \( A_{i} = W^P_L \). Note that we made no assumption on \( \phi \). The invariance of \( \phi \) allows to cut the problem into smaller blocks, independently of the structure of \( \phi \). This illustrate how symmetry can be used to better organize computation: if we can choose the points of evaluation, the computational cost can be alleviated by choosing them with some symmetry.

When \( \phi \) is invariant or equivariant, Equation (12) can be further reduced. If \( (\Lambda, \phi) \) is an invariant interpolation problem, it follows from Remark 1 that \( \phi(L_i) = 0 \) for any \( j > 1 \). Therefore for solving any invariant interpolation problem we only need to compute the first block of \( W^P_L \), i.e., the interpolant is given by \( A_{i}^{-1} \phi(L_i)^{t}(p_i)^{t} \).

More generally if \( (\Lambda, \phi) \) is a \( \theta - \theta \) equivariant problem, such that the irreducible representation \( \rho_{i} \) does not occur in \( \theta \), then \( \phi(L_i)^{t} = 0 \). The related block can thus be dismissed.

Example 5.3. Following on Example 3.2. Since we are interested in building an interpolation space for an invariant problem, we only need to compute bases of \( G \) and \( \mathbb{K}[x]^{G} \). We have \( L_G^G = \{ e_{G}, 2x_{G}^2, x_{G}^2 \} \) and \( \mathcal{P}^{G} = \{ 1, x_1 + x_2, x_1^2 + 2x_1x_2 + x_2^2, x_1^3 - 10x_1^2x_2 + 5x_1x_2^2 \} \). Since \( W^{P, G}_{L_G} \) is a square matrix with full rank, \( \text{span}_{\mathbb{K}}(\mathcal{P}^{G}) \) contains a unique invariant interpolant for any invariant interpolation problem. It has to be the least interpolant.

For \( \phi \) given in Example 3.2, one finds the interpolant \( p \) by solving the 5 \( \times \) 5 linear system \( W a = \phi(L_5^G) \). The solution \( a = (-0.333333, 3.295689, -36.593375, 45.36692) \) provides the coefficients of \( \mathcal{P}^{G} \) in \( p \). If \( p \) given above is only an approximation of the least interpolant, due to numerical inaccuracy, it is at least exactly invariant. Had we computed the least interpolant with the algorithm of [4], i.e., by elimination of the Vandermonde matrix based on the monomial basis, the least interpolant obtained would not be exactly invariant because of the propagation of numerical inaccuracies.

We define the deviation from invariance (ISD) of \( p = \sum_{\alpha} a_{x} \chi^{\alpha} \) as \( \sigma(a_{x}, a_{y}) + \sigma(a_{x}, a_{y}) + \sigma(a_{x}, a_{y}) + \sigma(a_{x}, a_{y}) + \sigma(\chi^{\alpha}, |\alpha|) \) where \( \sigma \) is the standard deviation, and \( \mathcal{B} \) represents the exponents of the monomials that do not belongs to any of the elements in \( \mathcal{P}^{G} \). In
Table 1 shows the ISD for the interpolant p computed with different precisions. The obtained polynomials are somehow far from being $G$-invariant.

$$\begin{array}{|c|c|c|c|c|}
\hline
\# \text{Digits} & 10 & 15 & 20 & 30 \\
\hline
\text{ISD} & 72.9614 & 40.0289 & 6.0967 & < 10^{-9} \\
\hline
\end{array}$$

Table 1: ISD values for different digits of precision

In the same spirit, let us mention that the condition number of $W^M$, where $M$ is the monomial basis of $K[x]_{\leq 5}$, is more than $10^2$ times the condition number of $W^{G^M}$. This is an indicator that two additional digits of precision are lost in the computation.

Example 5.4. Following up on Example 4.4, let $\theta$ be the permutation representation of $D_3$ in $\mathbb{R}^3$. $\theta$ decomposes into two irreducible representations, the trivial representation and the irreducible representation $\theta$ of dimension 2. Let $\phi: \Lambda \rightarrow \mathbb{R}^3$ a $\theta - \theta$ equivariant map determined by $\phi(p) = (1, -1, 5)^t$. For solving $(\Lambda, \phi)$ we need only consider the first and third block of the Vandermonde matrix computed in Example 4.4. The $\rho^*$ - $\theta$ equivariant map that solve $(\Lambda, \phi)$ is $P = (p_1, p_2, p_3)$ with:

$$p_1 := \frac{705}{4256} x_1^2 + \frac{135}{4256} x_2^2 + \frac{31}{56} \sqrt{3} x_1 x_2 + \frac{93}{56} x_2 - \frac{15}{112} \sqrt{3} x_1 x_2$$

$$p_2 := \frac{705}{4256} x_1^2 + \frac{135}{4256} x_2^2 + \frac{31}{56} \sqrt{3} x_1 x_2 - \frac{93}{56} x_2 + \frac{15}{112} \sqrt{3} x_1 x_2$$

$$p_3 := -\frac{75}{2128} x_1^2 + \frac{495}{2128} x_2^2 - \frac{31}{28} \sqrt{3} x_1.$$ 

In Figure 4 we show the image of $\mathbb{R}^2$ by $P$ and the tangency conditions imposed by $\phi$.

| $\lambda_1 = e_{11} + x_{11} - x_{12} - e_{21}$ |
| $\lambda_2 = 2(e_{11} + e_{12} + 2x_{11} + 2e_{12} + 2e_{21} - 2e_{22})$ |
| $\lambda_3 = 2(e_{11} + e_{12} + 2x_{11} + 2e_{12} - 2e_{21})$ |
| $\lambda_4 = 2(e_{11} + e_{12} - 2x_{11} + 2e_{12} - 2e_{21})$ |
| $\lambda_5 = (e_{11} + e_{12} + 2x_{11} + 2e_{12} + 2e_{21} + 2e_{22})$ |
| $\lambda_6 = (e_{11} + e_{12} + 2x_{11} + 2e_{12} - 2e_{21} - 2e_{22})$ |
| $\lambda_7 = (e_{11} + e_{12} - 2x_{11} + 2e_{12} - 2e_{21} - 2e_{22})$ |
| $\lambda_8 = (e_{11} + e_{12} - 2x_{11} + 2e_{12} + 2e_{21} + 2e_{22})$ |

The columns correspond to

$$g^3 := \left[ \begin{array}{c} x, x^2 - y^2, x^3 + xy^2, x^4 - y^4 \end{array} \right],$$

$$g^3 := \left[ \begin{array}{c} \frac{9y}{8960}, \sqrt{9y} - 90, \frac{9y}{8960}, \sqrt{9y} + 90 \end{array} \right].$$

We thus determine that the equivariant interpolant for the interpolation problem described in Example 3.6 is given by

$$p_1 = \frac{\alpha}{320} x + \frac{3y}{640} (x^2 - y^2) + \frac{9y}{8960} x(x^2 + y^2) + \frac{27}{17920} (x^4 - y^4)$$

$$p_2 = \frac{\alpha}{320} y - \frac{3y}{640} x + \frac{9y}{8960} (x^2 + y^2) - \frac{27}{17920} (x^4 + y^4)$$

where

$$\alpha = 5\sqrt{3}(25a - 114b) + 494d - 185c, \quad \beta = 5\sqrt{3}(114d - 25c) + 38b - 5a,$$

$$\gamma = 2\sqrt{3}(2b - 25a) + 185c - 182d, \quad \delta = 5\sqrt{3}(25a - 42d) + 5a - 14b.$$ 

REFERENCES


