The Euclidean Division as an Iterative ERES-based Process

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Abstract. Considering the Euclidean Division of two real polynomials, we present an iterative process based on the ERES method to compute the remainder of the division and we represent it using a simple matrix form.

Introduction

The representation of the Euclidean algorithm process is presented using the matrix-based methodology of Extended-Row-Equivalence and Shifting operations (ERES) [3, 4]. This allows the use of numerical methodologies for algebraic computation problems with the additional advantage of being able to handle uncertain coefficients and numerical errors.

We consider two real polynomials:

$$P(x) = \sum_{i=0}^{m} p_i \, x^i, \ p_m \neq 0 \quad \text{and} \quad Q(x) = \sum_{i=0}^{n} q_i \, x^i, \ q_n \neq 0, \quad m, n \in \mathbb{N} \tag{0.1}$$

with degrees $\deg\{P(x)\} = m$, $\deg\{Q(x)\} = n$ respectively, and $m \geq n$.

Definition 1. *We define the set*

$$\mathcal{D}_{m,n} = \Big\{ (P(x), Q(x)) : P(x), Q(x) \in \mathbb{R}[x], \ m = \deg\{P(x)\} \geq \deg\{Q(x)\} = n \Big\}$$

For any pair $\mathcal{D} = (P(x), Q(x)) \in \mathcal{D}_{m,n}$, we define a vector representative $\underline{D}(x)$ and a basis matrix D_m represented as :

$$\underline{D}(x) = [P(x), Q(x)]^t = [\underline{p}, \underline{q}]^t \cdot \underline{e}_m(x) = D_m \cdot \underline{e}_m(x)$$

where $D_m \in \mathbb{R}^{2\times(m+1)}$, $\underline{e}_m(x) = [x^m, x^{m-1}, \ldots, x, 1]^t$. The matrix D_m is formed directly from the coefficients of the given polynomials $P(x)$ and $Q(x)$.

Definition 2. *Given a pair $\mathcal{D}_{m,n}$ of real polynomials with a basis matrix D_m the following operations are defined [3, 4]:*

a) Elementary row operations with scalars from $\mathbb{R}$ *on* D_m .
b) Addition or elimination of zero rows on D_m .
c) If $\underline{a}^t = [0, \ldots, 0, a_l, \ldots, a_k] \in \mathbb{R}^k$, $a_l \neq 0$ *then we define as the* Shifting *operation*

$$shf : \mathrm{shf}(\underline{a}^t) = [a_l, \ldots, a_k, 0, \ldots, 0] \in \mathbb{R}^k$$

By $\mathrm{shf}(\mathcal{D}_{m,n}) \equiv \mathcal{D}^*_{m,n}$*, we shall denote the pair obtained from* $\mathcal{D}_{m,n}$ *by applying shifting on the rows of* D_m*. Type (a), (b) and (c) operations are referred to as* Extended-Row-Equivalence and Shifting *(ERES) operations.*

The following theorem shows the relation between a matrix and its shifted form [1] .

Theorem 1 (Matrix representation of Shifting). *If* $D \in \mathbb{R}^{2\times k}$*,* $k > 2$*, is an upper trapezoidal matrix with rank* $\rho(D) = 2$ *and* $D^* \in \mathbb{R}^{2\times k}$ *is the matrix obtained from* D *by applying shifting on its rows, then there exists a matrix* $S \in \mathbb{R}^{k\times k}$ *such that:* $D^* = D \cdot S$.

Corollary 1. *If* $D_m \in \mathbb{R}^{2\times(m+1)}$ *is the basis matrix of a pair of real polynomials* $\mathcal{D} = (P(x), Q(x)) \in \mathcal{D}_{m,n}$*, then* $D^*_m \in \mathbb{R}^{2\times(m+1)}$ *is the basis matrix of the pair* $\mathcal{D}^* = (P(x), x^{m-n}\, Q(x)) \in \mathcal{D}_{m,m}$ *and there exists a matrix* $S_{\mathcal{D}} \in \mathbb{R}^{(m+1)\times(m+1)}$ *such that:*

$$D^*_m = D_m \cdot S_{\mathcal{D}} \tag{0.2}$$

The ERES representation of the Euclidean Division

If we have a pair of polynomials $\mathcal{D} = (P(x), Q(x)) \in \mathcal{D}_{m,n}$, then, according to Euclid's division algorithm, it holds:

$$P(x) = \frac{p_m}{q_n}\, x^{m-n}\, Q(x) + R_1(x) \tag{0.3}$$

This is the first and basic step of the Euclidean Division algorithm. The polynomial $R_1(x) \in \mathbb{R}[x]$ is given by:

$$R_1(x) = \sum_{i=m-n}^{m-1} \left(p_i - \frac{p_m}{q_n} q_{i-(m-n)} \right) x^i + \sum_{i=0}^{m-n-1} p_i\, x^i \tag{0.4}$$

In the following, we will show that the remainder $R_1(x)$ can be computed by applying ERES operations to the basis matrix D_m of the pair $\mathcal{D}$.

Proposition 1 (Matrix representation of the first remainder of the Euclidean Division). *Applying the algorithm of the Euclidean Division to a pair* $\mathcal{D} = (P(x), Q(x)) \in \mathcal{D}_{m,n}$ *of real polynomials, there exists a polynomial* $R_1(x) \in \mathbb{R}[x]$ *with degree* $0 \leq deg\{R_1(x)\} < m$ *such that:*

$$P(x) = \frac{p_m}{q_n}\, x^{m-n}\, Q(x) + R_1(x)$$

Then, the remainder $R_1(x)$ can be represented in matrix form as:

$$R_1(x) = \underline{v}^t \cdot E_1 \cdot \underline{e}_m(x)$$

where $E_1 \in \mathbb{R}^{2\times(m+1)}$ is the matrix, which occurs from the application of the ERES operations on the basis matrix D_m of the pair $\mathcal{D}$ and $\underline{v} = [0,\ 1]^t$.

Proof. If we consider the division $P(x)/Q(x)$, then, according to Euclid's algorithm, there is a polynomial $R_1(x)$ with degree $0 \leq deg\{R_1(x)\} < m$ such that:

$$R_1(x) \;=\; P(x) - \frac{p_m}{q_n}\, x^{m-n}\, Q(x) \;=\; [0,\ 1] \cdot \begin{bmatrix} 0 & 1 \\ 1 & -\frac{p_m}{q_n} \end{bmatrix} \cdot \begin{bmatrix} P(x) \\ x^{m-n}\, Q(x) \end{bmatrix} \tag{0.5}$$

If we take into account the result in corollary 1, we will have:

$$R_1(x) \;=\; [0,\ 1] \cdot \begin{bmatrix} 0 & 1 \\ 1 & -\frac{p_m}{q_n} \end{bmatrix} \cdot D_m \cdot S_{\mathcal{D}} \cdot \underline{e}_m(x) \;=\; \underline{v}^t \cdot C \cdot D_m \cdot S_{\mathcal{D}} \cdot \underline{e}_m(x) \tag{0.6}$$

where $\underline{v}^t = [0,\ 1]$, $C = \begin{bmatrix} 0 & 1 \\ 1 & -\frac{p_m}{q_n} \end{bmatrix}$, D_m is the basis matrix of the polynomials $P(x)$ and $Q(x)$ and $S_{\mathcal{D}}$ the respective shifting matrix. Therefore, there exists a matrix $E_1 \in \mathbb{R}^{2\times(m+1)}$ such that:

$$E_1 = C \cdot D_m \cdot S_{\mathcal{D}} \quad \text{and} \quad R_1(x) = \underline{v}^t \cdot E_1 \cdot \underline{e}_m(x) \tag{0.7}$$

We consider now the basis matrix D_m of the polynomials $P(x)$ and $Q(x)$:

$$D_m = \begin{bmatrix} P(x) \\ Q(x) \end{bmatrix} = \begin{bmatrix} p_m & \ldots & p_{n+1} & p_n & p_{n-1} & \ldots & p_0 \\ 0 & \ldots & 0 & q_n & q_{n-1} & \ldots & q_0 \end{bmatrix} \cdot \underline{e}_m(x) \tag{0.8}$$

and we will show that the above matrix E_1 is produced by applying the ERES operations to the basis matrix D_m of the polynomials $P(x)$ and $Q(x)$. We follow the next methodology:

1. We apply shifting on the rows of D_m. Let $S_{\mathcal{D}} \in \mathbb{R}^{(m+1)\times(m+1)}$, be the proper shifting matrix: $D_m^{(1)} = D_m \cdot S_{\mathcal{D}} = \begin{bmatrix} p_m & \cdots & p_{m-n+1} & p_{m-n} & p_{m-n-1} & \cdots & p_0 \\ q_n & \cdots & q_1 & q_0 & 0 & \ldots & 0 \end{bmatrix}$
2. We reorder the rows of the matrix $D_m^{(1)}$. If $J = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ is the permutation matrix, then: $D_m^{(2)} = J \cdot D_m^{(1)} = \begin{bmatrix} q_n & \cdots & q_1 & q_0 & 0 & \ldots & 0 \\ p_m & \cdots & p_{m-n+1} & p_{m-n} & p_{m-n-1} & \cdots & p_0 \end{bmatrix}$
3. We apply stable row operations on $D_m^{(2)}$ (LU factorization). If $L = \begin{bmatrix} 1 & 0 \\ \frac{p_m}{q_n} & 1 \end{bmatrix}$ then $L^{-1} = \begin{bmatrix} 1 & 0 \\ -\frac{p_m}{q_n} & 1 \end{bmatrix}$ and therefore:

$$D_m^{(3)} = L^{-1} \cdot D_m^{(2)} = \begin{bmatrix} 1 & 0 \\ -\frac{p_m}{q_n} & 1 \end{bmatrix} \cdot \begin{bmatrix} q_n & \cdots & q_1 & q_0 & 0 & \cdots & 0 \\ p_m & \cdots & p_{m-n+1} & p_{m-n} & p_{m-n-1} & \cdots & p_0 \end{bmatrix}$$

$$= \begin{bmatrix} q_n & \cdots & q_1 & q_0 & 0 & \cdots & 0 \\ 0 & \cdots & p_{m-n+1} - q_1 \frac{p_m}{q_n} & p_{m-n} - q_0 \frac{p_m}{q_n} & p_{m-n-1} & \cdots & p_0 \end{bmatrix}$$

We notice that the term $\frac{p_m}{q_n}$ emerges from the LU factorization.

The above process can be described by the following equation:

$$D_m^{(3)} = L^{-1} \cdot J \cdot D_m \cdot S_{\mathcal{D}} \tag{0.9}$$

which represents the ERES methodology. Obviously $L^{-1} \cdot J = C$ and therefore, we conclude that $D_m^{(3)} \equiv E_1$. □

The following theorem establishes the connection between the ERES method and the Euclidean Division of two real polynomials.

Theorem 2 (Matrix representation of the remainder of the Euclidean Division). *Applying the algorithm of the Euclidean Division to a pair* $\mathcal{D} = (P(x), Q(x)) \in \mathcal{D}_{m,n}$ *of real polynomials, there are polynomials* $G(x)$, $R(x) \in \mathbb{R}[x]$ *with degrees* $deg\{G(x)\} = m - n$ *and* $0 \leq deg\{R(x)\} < n$ *respectively, such that:*

$$P(x) = G(x)\, Q(x) + R(x)$$

Then, the final remainder $R(x)$ *can be represented in matrix form as:*

$$R(x) = \underline{v}^t \cdot E_N \cdot \underline{e}_m(x)$$

where $E_N \in \mathbb{R}^{2\times(m+1)}$ *is the matrix, which occurs from the successive application of the ERES operations on the basis matrix* D_m *of the pair* $\mathcal{D}$ *and* $\underline{v} = [0,\ 1]^t$.

The proof of the previous theorem is based on the iterative application of the result from proposition 1 to the sequence $\{(P(x), Q(x)),\ (R_i(x), Q(x))\}$, for $1 \leq i \leq (m-n)$. Therefore, we get a sequence of matrices $E_i = L_i^{-1} \cdot E_{i-1} \cdot S_i$, for $i = 1, 2, \ldots, N < m - n$, where the final matrix E_N gives the total remainder $R(x)$ and every matrix L_i gives a specific coefficient of the quotient $G(x)$.

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