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Computing the Kalman form

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Abstract

We present two algorithms for the computation of the Kalman form of a linear control system. The first one is based on the technique developed by Keller-Gehrig for the computation of the characteristic polynomial. The cost is a logarithmic number of matrix multiplications. To our knowledge, this improves the best previously known algebraic complexity by an order of magnitude. Then we also present a cubic algorithm proven to be more efficient in practice.

1 Introduction

This report is a continuation of a collaboration with Aude Rondepierre on the algorithmic similarities between the computation of the Kalman form and of the characteristic polynomial. This collaboration led to [DR05, Theorem 2]. We report here an improvement of this last result based on a remark by the second author.

For a definition of the Kalman form of a linear control system, see [Kal61, Theorem 1]. In this report we show how to adapt the branching algorithm of Keller-Gehrig [KG85, §5] (computing the characteristic polynomial) to compute the Kalman form. This implies an algebraic time complexity of $\mathcal{O}(n^\omega \log n)$. Now, the discussion of [DPW05, §2] shows that a cubic algorithm, LUK, is more efficient in practice for the computation of the characteristic polynomial. Therefore, we adapt it to the computation of the Kalman form.

The outline of this report is the following : in section 2 we recall the principle of the branching algorithm of Keller-Gehrig. Then we decompose the computation of the Kalman form into two steps : the computation of the so-called “compressed Krylov matrix” and the computation of the Kalman form itself. For the first step, the algorithm of Keller-Gehrig is easily adapted in 3.1.1. Alternatively the same computation can be performed by an adaptation of the algorithm LUK as shown in 3.1.2. Now, the recovery of the Kalman form from this compressed Krylov matrix also uses the technique of LUK algorithm in section 3.2.1. Lastly, algorithm 3.2.2 merges the ideas of sections 3.1.2 and 3.2.1 but removes some unnecessary operations.

2 Keller-Gehrig's branching algorithm

2.1 Principle

Consider the $n \times n^2$ Krylov matrix K generated by the n column vectors of the identity matrix iterated with the matrix A (of order n) :

$$K = [e_1 \mid \dots \mid A^{n-1}e_1 \mid \dots \mid e_n \mid \dots \mid A^{n-1}e_n]$$

The rank of K is n . Let us form the $n \times n$ non-singular matrix \overline{K} by picking the first n linearly independent rows of K .

If a column vector $A^k e_j$ is linearly dependent with the previous iterates, then any vector $A^l e_j, l > k$ will also be linearly dependent. Consequently the matrix \overline{K} has the form :

$$\overline{K} = [e_1 \mid \dots \mid A^{d_1}e_1 \mid \dots \mid e_m \mid \dots \mid A^{d_m}e_m] \quad (1)$$

with $0 \leq d_i \leq n - 1$.

Property 1. The matrix $\overline{K}^{-1} A \overline{K}$ has the Hessenberg polycyclic form : it is block upper triangular, with companions blocks on its diagonal, and the upper blocks are zero except on their last column.

$$\overline{K}^{-1} A \overline{K} = \begin{bmatrix} \boxed{\begin{matrix} 0 & & * \\ 1 & 0 & * \\ & \ddots & \ddots & * \\ & & 1 & * \end{matrix}} & & * \\ & \ddots & * \\ & & \boxed{\begin{matrix} 0 & & * \\ 1 & 0 & * \\ & \ddots & \ddots & * \\ & & 1 & * \end{matrix}} & * \end{bmatrix} \quad (2)$$

Corollary 1. The characteristic polynomial of A is the product of the polynomials associated with the companion blocks of the diagonal of H .

2.2 The algorithm

Ingredients :

- The position of the linearly independent columns is given by a gaussian elimination. A block elimination is mandatory to reduce the algebraic complexity to matrix multiplication. Keller-Gehrig introduced in [KG85, §4] an algorithm called "step form elimination". The more recent literature replaced it by the row echelon elimination (for example in [CBS97]). We showed in [DPW05] that the LQUP (defined by in [IMH82]) elimination of \overline{K}^T (algorithm 2.2.1) could also be used.

Algorithm 2.2.1 ColReducedForm

Require: A a $m \times n$ matrix of rank r ($m, n \geq r$) over a field

Ensure: A' a $m \times r$ matrix formed by r linearly independent columns of A

1: $(L, Q, U, P, r) = \text{LQUP}(A^T)$ ($r = \text{rank}(A)$)

2: return $([I_r, 0](Q^T A^T))^T$

- The computation of the matrix K is prohibitive (n^3 coefficients and $\mathcal{O}(n^4)$ arithmetic operations with standard matrix product). Hence, the elimination process must be combined within the building of the matrix.

- The computation of the iterates can rely on matrix multiplication, by computing the $\lceil \log_2(n) \rceil$ following powers of A :

$$A, A^2, \dots, A^{2^i}, A^{2^{\lceil \log_2(n) \rceil - 1}}$$

Thus the following scheme

$$\begin{cases} V_0 &= [e_j] \\ V_{i+1} &= [V_i | A^{2^i} V_i] \end{cases} \quad (3)$$

computes every iterates of e_j in $\mathcal{O}(n^\omega \log n)$ operations.

- One elimination is performed after each application of A^{2^i} , to discard the linearly dependent iterates for the next iteration step. Moreover if a vector e_j has only $k < 2^i$ linearly independent iterates, one can stop the computation of its iterates. Therefore, the scheme (3) will only be applied on the block iterates of size 2^i .

The algorithm is the following :

Algorithm 2.2.2 Characteristic Polynomial [Keller-Gehrig]

Require: A a $n \times n$ matrix over a field

Ensure: P_{char}^A the characteristic polynomial of A

```

1:  $i = 0$  ;  $V_0 = I_n = [V_{0,1} | V_{0,2} | \dots | V_{0,n}]$ 
2:  $B = A$ 
3: while ( $\exists k, V_{i,k}$  has  $2^i$  columns) do
4:   for all  $j$  do
5:     if ( $V_{i,j}$  has strictly less than  $2^i$  columns ) then
6:        $W_j = V_{i,j}$ 
7:     else
8:        $W_j = [V_{i,j} | B V_{i,j}]$ 
9:     end if
10:  end for
11:   $W = [W_1 | \dots | W_n]$ 
12:   $V_{i+1} = \text{ColReducedForm}(W)$   $\{V_{i+1} = [V_{i+1,1} | \dots | V_{i+1,n}]$  where  $V_{i+1,j}$  are the remaining
    vectors of  $W_j$  in  $V_{i+1}\}$ 
13:   $B = B \times B$  ;  $i = i + 1$ 
14: end while
15:  $F = V^{-1} A V$ ,  $F$  is as in (2)
16:  $f = \prod_i f_i$  where  $f_i$  is the polynomial of the  $i$ th companion block of  $F$ 
17: return  $f$ 

```

3 Application to the computation of the Kalman form

In the following, we will show that the algebraic time complexity for the computation of the Kalman form given in [DR05, Theorem 2] can be improved by an order of magnitude by adapting the branching algorithm of Keller-Gehrig. Let us decompose the computation of the Kalman form into two steps :

- the computation of the compressed Krylov matrix \overline{K} from equation 1 (part 3.1).
- The computation of the Kalman form itself (part 3.2.1)

The first step can be done using either Keller-Gehrig technique (section 3.1.1) or using LUK (section 3.1.2). In both situations, some computations can be saved by merging the two steps, as we do in section 3.2.2, since they share common operations.

3.1 Computation of the compressed Krylov matrix

3.1.1 A la Keller-Gehrig

Algorithm 3.1.1 KGCKM Compressed Krylov Matrix (Keller-Gehrig)

Require: A a $n \times n$ matrix over a field, B , a $n \times m$ matrix

Ensure: $(V, \text{rank}(V))$ as in (1)

```

1:  $i = 0$ 
2:  $V_0 = B = (V_{0,1}, V_{0,2}, \dots, V_{0,m})$ 
3:  $C = A$ 
4: while  $(\exists k, V_k$  has  $2^i$  columns) do
5:   for all  $j$  do
6:     if  $(V_{i,j}$  has strictly less than  $2^i$  columns) then
7:        $W_j = V_{i,j}$ 
8:     else
9:        $W_j = [V_{i,j} | CV_{i,j}]$ 
10:    end if
11:  end for
12:   $W = [W_1 | \dots | W_n]$ 
13:   $V_{i+1} = \text{ColReducedForm}(W)$  remember  $r = \text{rank}(W)$   $\{V_{i+1} = [V_{i+1,1} | \dots | V_{i+1,n}]$  where
     $V_{i+1,j}$  are the remaining vectors of  $W_j$  in  $V_{i+1}\}$ 
14:   $C = C \times C$ 
15:   $i = i + 1$ 
16: end while
17: return  $(V_i, r)$ 

```

The idea in algorithm 3.1.1 is just to replace the identity matrix I_n by the matrix B in algorithm 2.2.2. Then, the last computed V_i is formed by some column vectors of B and their iterates with the matrix A . This matrix is a basis of $\text{Span}(B, AB, \dots, A^{n-1}B)$.

3.1.2 A la LU-Krylov

Algorithm 3.1.2 presents another method to compute \overline{K} , adapted from [DPW05, algorithm 2.2]. This algorithm is not as good in theory ($\mathcal{O}(n^3)$ versus $\mathcal{O}(n^\omega \log n)$), but proven to be more efficient in practice [DPW05, §2.4]. Its correctness can be proven in the same way as for algorithm 3.2.1.

3.2 Computation of the kalman form

3.2.1 From the compressed Krylov matrix

Using the technique of algorithm LUK ([DPW05, theorem 2.1]), the matrix T can be recovered by completing the compressed Krylov matrix \overline{K} into an invertible matrix. This can be easily done by a triangularization of \overline{K}^T as follows : one computes the LUP factorization of \overline{K}^T , and replace $[U_1 U_2]$ by $\begin{bmatrix} U_1 & U_2 \\ 0 & Id \end{bmatrix}$ and $[L]$ by $\begin{bmatrix} L & 0 \\ 0 & Id \end{bmatrix}$. This simply corresponds to set

$$T = \left[\overline{K} \mid P^T \begin{bmatrix} 0 \\ I_{n-r} \end{bmatrix} \right].$$

Theorem 1. Let A and B be two matrices of dimension respectively $n \times n$ and $n \times m$. Let r be the rank of $\text{Span}(B, AB, \dots, A^{n-1}B)$. Algorithm 3.2.1 computes the Kalman form :

$$T^{-1}AT = \begin{bmatrix} H & C_1^T \\ 0 & C_2^T \end{bmatrix}, \begin{bmatrix} B_1 \\ 0 \end{bmatrix} = T^{-1}B$$

Algorithm 3.1.2 LUKCKM : Compressed Krylov Matrix (LU-Krylov)

Require: A a $n \times n$ matrix over a field, B , a $n \times m$ matrix

Ensure: $(V, \text{rank}(V))$ as in (1)

```
1:  $v = B_1$ 
2:  $\left\{ \begin{array}{l} K = [v \quad Av \quad A^2v \quad \dots] \\ (L, [U_1|U_2], P) = \text{LUP}(K^T), r_1 = \text{rank}(K) \end{array} \right\}$  {The matrix  $K$  is computed on the fly : at most  $2r_1$  columns are computed.  $U_1$  is  $r_1 \times r_1$ }
3: if  $(r_1 = n)$  then
4:   return  $(K, r_1)$ 
5: else
6:    $A' = PAP^T = \begin{bmatrix} A'_{11} & A'_{12} \\ A'_{21} & A'_{22} \end{bmatrix}$  where  $A'_{11}$  is  $r_1 \times r_1$ .
7:    $A_R = A'_{22} - U_2^T U_1^{-T} A'_{12}$ 
8:    $B' = \begin{bmatrix} L^{-T} & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} U_1^{-T} & 0 \\ -U_2^T U_1^{-T} & I \end{bmatrix} PB$ 
9:   Compute the permutation  $Q$  s.t.  $B'Q = \begin{bmatrix} X & Y \\ 0 & Z \end{bmatrix}$ 
10:   $(V_2, r_2) = \text{LUCKM}(A_R, Z)$ 
11:   $V = \left[ K \mid P^T \begin{bmatrix} 0 \\ V_2 \end{bmatrix} \right]$ 
12:  return  $(V, r_1 + r_2)$ 
13: end if
```

Algorithm 3.2.1 Kalman form

Require: A a $n \times n$ matrix over a field, B , a $n \times m$ matrix

Ensure: r, T, H, C_1, C_2, B_1 as in theorem 1

```
1:  $(V, r) = \text{CompressedKrylovMatrix}(A, B)$ 
2: if  $(r=n)$  then
3:   return  $(n, Id, A, \emptyset, \emptyset, B)$ 
4: else
5:    $(L, [U_1|U_2], P) = \text{LUP}(V^T)$ 
6:    $T = \left[ V \mid P^T \begin{bmatrix} 0 \\ I_{n-r} \end{bmatrix} \right]$ 
7:    $B_1 = L^{-T} U_1^{-T} PB$ 
8:    $A' = PA^T P^T = \begin{bmatrix} A'_{11} & A'_{12} \\ A'_{21} & A'_{22} \end{bmatrix}$ 
9:    $C_1 = L^{-T} U_1^{-T} A'_{12}$ 
10:   $C_2 = A'_{22} - U_2^T U_1^{-T} A'_{12}$ 
11:  for all  $j$  do
12:    Let  $t_j$  be the column indexes in  $V$  of the last iterate of the  $j$ th block.
13:    Let  $l_j$  be first linearly dependent row of the  $j$ th block in  $L$  (to be stored during the execution of CompressedKrylovMatrix)
14:     $m_j = l_j L_{1..t_j, 1..t_j}^{-1}$ 
15:  end for
16:  Build the polycyclic matrix  $H$  by placing each column vectors  $m_j$  at column index  $t_j$  and adding 1 on the subdiagonal on all other columns.
17:  return  $(r, T, H, C_1, C_2, B_1)$ 
18: end if
```

where H and B_1 are respectively $r \times r$ et $r \times m$.

It requires $\mathcal{O}(n^\omega \log n)$ field operations using algorithm 3.1.1 or $\mathcal{O}(n^3)$ using algorithm 3.1.2.

Proof. Algorithm `CompressedKrylovMatrix` builds the matrix V satisfying

$$AV = VH$$

where H has the Hessenberg polycyclic form (2).

Now

$$\begin{aligned} AT &= \left[AV \mid AP^T \begin{bmatrix} 0 \\ I_{n-r} \end{bmatrix} \right] \\ &= T \begin{bmatrix} H & C_1 \\ 0 & C_2 \end{bmatrix} \end{aligned}$$

with $T \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = AP^T \begin{bmatrix} 0 \\ I_{n-r} \end{bmatrix}$. Let us write

$$A' = PAP^T = \begin{bmatrix} A'_{11} & A'_{12} \\ A'_{21} & A'_{22} \end{bmatrix}.$$

We have

$$T \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = P^T A' \begin{bmatrix} 0 \\ I_{n-r} \end{bmatrix} = P^T \begin{bmatrix} A'_{12} \\ A'_{22} \end{bmatrix}$$

Now

$$T = P^T \begin{bmatrix} U_1^T & 0 \\ U_2^T & I_{n-r} \end{bmatrix} \begin{bmatrix} L^T & 0 \\ 0 & I_{n-r} \end{bmatrix},$$

therefore

$$\begin{aligned} \begin{bmatrix} U_1^T & 0 \\ U_2^T & I_{n-r} \end{bmatrix} \begin{bmatrix} L^T & 0 \\ 0 & I_{n-r} \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} &= \begin{bmatrix} A'_{12} \\ A'_{22} \end{bmatrix} \\ \begin{bmatrix} U_1^T & 0 \\ U_2^T & I_{n-r} \end{bmatrix} \begin{bmatrix} L^T C_1 \\ C_2 \end{bmatrix} &= \begin{bmatrix} A'_{12} \\ A'_{22} \end{bmatrix} \end{aligned}$$

And the system

$$\begin{cases} U_1^T L^T C_1 &= A'_{12} \\ U_2^T L^T C_1 + C_2 &= A'_{22} \end{cases}$$

has the following solution

$$\begin{cases} C_1 &= L^{-T} U_1^{-T} A'_{12} \\ C_2 &= A'_{22} - U_2^T U_1^{-T} A'_{12} \end{cases}$$

Lastly

$$T^{-1}AT = \begin{bmatrix} H & C_1 \\ 0 & C_2 \end{bmatrix},$$

The column vectors of B are linear combinations of the column vectors of V , therefore we can write

$$B = T \begin{bmatrix} B_1 \\ 0 \end{bmatrix}$$

and then

$$B_1 = L^{-T} U_1^{-T} P B.$$

If `CompressedKrylovMatrix` is done by algorithm 3.1.1, it requires $\mathcal{O}(n^\omega \log n)$ field operations : at most $\log n$ executions of the while loop whose domining operation is $B = B \times B$ in n^ω . Any remaining operation can be done in $\mathcal{O}(n^\omega)$.

Yet if `CompressedKrylovMatrix` is done by algorithm 3.1.2, the Krylov matrix is computed by at most n matrix-vector products ($\mathcal{O}(n^2)$ each) and any remaining operation can be done in $\mathcal{O}(n^3)$ using classic matrix arithmetic.

□

3.2.2 Improvements

Using Keller-Gehrig variant : One can note that the LUP factorization of V is already available at the end of algorithm 3.1.1. Thus, step 5 in algorithm 3.2.1 can be skipped.

Using LUK variant : Here again, one can merge the common operations between algorithms 3.1.2 and 3.2.1 into algorithm 3.2.2. More precisely, every operation is already done in algorithm 3.1.2 except the update of the upper right hand side block of H (denoted by J_1 in algorithm 3.2.2). However, we intentionally forgot to explain how to compute it in the previous combination of algorithms 3.1.2 and 3.2.1 and precise it here. Note that this computation of J_1 should be improved, taking into account its structure : a few non zero columns, since it is a submatrix of the Hessenberg polycyclic matrix H .

Algorithm 3.2.2 Kalman-LUK : Kalman-LU-Krylov

Require: A a $n \times n$ matrix over a field, B , a $n \times m$ matrix

Ensure: r_1, T, H, C_1, C_2, B_1 as in theorem 1

```

1:  $v = B_1$ 
2:  $\left\{ \begin{array}{l} K = [v \quad Av \quad A^2v \quad \dots] \\ (L, [U_1|U_2], P) = \text{LUP}(K^T), r_1 = \text{rank}(K) \end{array} \right\}$  {The matrix  $K$  is computed on the fly : at most
    $2r_1$  columns are computed}
3:  $m = (m_1, \dots, m_{r_1}) = L_{r_1+1} L_{1\dots r_1}^{-1}$ 
4:  $f = X^{r_1} - \sum_{i=1}^{r_1} m_i X^{i-1}$ 
5: if  $(r_1 = n)$  then
6:   return  $(n, Id, A, \emptyset, \emptyset, B)$ 
7: else
8:    $A' = PAP^T = \begin{bmatrix} A'_{11} & A'_{12} \\ A'_{21} & A'_{22} \end{bmatrix}$  where  $A'_{11}$  is  $r_1 \times r_1$ .
9:    $A_R = A'_{22} - U_2^T U_1^{-T} A'_{12}$ 
10:   $B' = \begin{bmatrix} L^{-T} & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} U_1^{-T} & 0 \\ -U_2^T U_1^{-T} & I \end{bmatrix} PB$ 
11:  Compute the permutation  $Q$  s.t.  $B'Q = \begin{bmatrix} X & Y \\ 0 & Z \end{bmatrix}$  { $Z$  is  $\mu \times \mu$ }
12:  if  $(\mu = 0)$  then
13:     $C_1 = L^{-T} U_1^{-T} A'_{12}$ 
14:     $C_2 = A_R$ 
15:     $T = \left[ K \mid P^T \begin{bmatrix} 0 \\ I_{n-r_1} \end{bmatrix} \right]$ 
16:    return  $(r_1, T, C_f, C_1, C_2, X)$ 
17:  else
18:     $(r_2, T^{(2)}, H^{(2)}, C_1^{(2)}, C_2^{(2)}, B_1^{(2)}) = \text{Kalman-LUK}(A_R, Z)$ 
19:     $T = \left[ K \mid P^T \begin{bmatrix} 0 \\ T^{(2)} \end{bmatrix} \right]$ 
20:     $J = L^{-T} U_1^{-T} A'_{12} T^{(2)} = [J_1 \quad J_2]$  { $J_1$  is  $r_1 \times r_2$  and  $J_2$ ,  $r_1 \times (n - r_1 - r_2)$ }
21:     $H = \begin{bmatrix} C_f & J_1 \\ 0 & H^{(2)} \end{bmatrix}$ 
22:     $C_1 = \begin{bmatrix} J_2 \\ C_1^{(2)} \end{bmatrix}$ 
23:    return  $(r_1 + r_2, T, H, C_1, C_2^{(2)}, B_1)$ 
24:  end if
25: end if

```

Algorithm 3.2.2 is still $\mathcal{O}(n^3)$ since the additional operations are the following :

- the computation of L^{-T} in $\mathcal{O}(r_1^3)$
- the matrix product $(L^{-T}U_1^{-T}A'_{12}) \times T^{(2)}$ in $\mathcal{O}(r_1(n - r_1)^2)$

Summing for every recursive level, one gets $\mathcal{O}(n^3)$ since the sum of the r_1 of each recursive level is n .

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