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DIPLOMOVÁ PRÁCE

Minimal Problem Solver Generator

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May 5, 2015

Lze získat na
<http://cmp.felk.cvut.cz/~trutmpav/theses/bsc-pavel-trutman.pdf>

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Acknowledge grants here. Use centering if the text is too short.

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BACHELOR PROJECT ASSIGNMENT

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Study programme: Cybernetics and Robotics

Specialisation: Robotics

Title of Bachelor Project: Minimal Problem Solver Generator

Guidelines:

1. Review the state of the art in solving the polynomial systems using linear algebra [1, 2] and the automatic generator of the polynomial solvers [3, 4].
2. Implement the improvement [4] of [3] into the existing automatic generator of solvers.
3. Implement a variation of algorithm [1], review its behavior, and suggest how to take over some of its elements to the automatic generator and implement it.
4. Demonstrate the functionality of the new solver generator and compare it with the original solver.

Bibliography/Sources:

- [1] Faugere, J.-C. (June 1999): "A new efficient algorithm for computing Gröbner bases (F4)". Journal of Pure and Applied Algebra (Elsevier Science) 139 (1): 61–88.
doi:10.1016/S0022-4049(99)00005-5. ISSN 0022-4049.
- [2] Faugere, J.-C. (July 2002): "A new efficient algorithm for computing Gröbner bases without reduction to zero (F5)". Proceedings of the 2002 international symposium on Symbolic and algebraic computation (ISSAC) (ACM Press): 75–83.
- [3] Kukelova, Z.: Algebraic Methods in Computer Vision. PhD Thesis. CTU in Prague 2013.
<http://cmp.felk.cvut.cz/~kukelova/webthesis/docs/Kukelova-phd-2013.pdf>
- [4] Kukelova, Z.; Bujnak, M.; Heller, J.; Pajdla, T.: Singly-Bordered Block-Diagonal Form for Minimal Problem Solvers. ACCV 2014.

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Prague, December 9, 2014

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

Student: Pavel T r u t m a n

Studijní program: Kybernetika a robotika (bakalářský)

Obor: Robotika

Název tématu: Generátor řešení minimálních problémů

Pokyny pro vypracování:

1. Prozkoumejte současné metody řešení polynomiálních rovnic [1, 2] a automatický generátor postupu řešení [3, 4].
2. Implementujte vylepšení [4] generátoru [3] do existujícího generátoru postupů řešení.
3. Implementujte variaci algoritmu [1], experimentujte s jeho chováním a navrhněte, co převzít z [1] do implementace generátoru a implementujte to.
4. Demonstrujte funkčnost nového generátoru postupu řešení a porovnejte ji se starým generátorem.

Seznam odborné literatury:

- [1] Faugere, J.-C. (June 1999): "A new efficient algorithm for computing Gröbner bases (F4)". Journal of Pure and Applied Algebra (Elsevier Science) 139 (1): 61–88.
doi:10.1016/S0022-4049(99)00005-5. ISSN 0022-4049.
- [2] Faugere, J.-C. (July 2002): "A new efficient algorithm for computing Gröbner bases without reduction to zero (F5)". Proceedings of the 2002 international symposium on Symbolic and algebraic computation (ISSAC) (ACM Press): 75–83.
- [3] Kukulova, Z.: Algebraic Methods in Computer Vision. PhD Thesis. CTU in Prague 2013.
<http://cmp.felk.cvut.cz/~kukulova/webthesis/docs/Kukulova-phd-2013.pdf>
- [4] Kukulova, Z.; Bujnak, M.; Heller, J.; Pajdla, T.: Singly-Bordered Block-Diagonal Form for Minimal Problem Solvers. ACCV 2014.

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Acknowledgements

I would like to thank my advisor Tomáš Pajdla for introducing me into Gröbner basis methods for solving polynomial systems and for his guidance and advices which enabled me to finish this thesis. I would also like to thank Zuzana Kúkelová for presenting me the automatic generator and for her comments to my improvements. Special thanks go to my family for all their support.

Author's declaration

I declare that I have work out the presented thesis independently and that I have listed all information sources used in accordance with the Methodical Guidelines about Maintaining Ethical Principles for Writing Academic Theses.

Prohlášení autora práce

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze dne

.....

Podpis autora práce

Abstract

Many problems in computer vision lead to polynomial systems solving. Therefore, we need an easy way how to generate an efficient solver for each problem. On this purpose the automatic generator has been presented. In this thesis we improve the automatic generator so we will be able to generate more efficient and numerically stable solvers.

To improve the automatic generator we review and implement some methods used in the state of the art Gröbner basis solvers. Especially, we focus on the F_4 Algorithm by Jean-Charles Faugère. Solvers, generated by the automatic generator, can be speed up when efficient methods are used to work with sparse matrices. We describe and implement method which is based on matrix partitioning. This method significantly speeds up the Gauss-Jordan elimination of sparse matrices.

We demonstrate the enhancements of the automatic generator on several important minimal problems. We show that the solvers generated by the new automatic generator are faster and numerically more stable than the solvers generated by the old version of the automatic generator.

Keywords: computer vision, robotics, minimal problems, polynomials equations, Gröbner basis

Abstrakt

Mnoho problémů v počítačovém vidění vede na řešení polynomiálních rovnic. Proto potřebujeme jednoduchý způsob, jak generovat efektivní postupy řešení každého z problémů. Z toho důvodu byl představen automatický generátor. V této práci vylepšíme automatický generátor, takže budeme schopni generovat ještě rychlejší a numericky stabilnější postupy řešení polynomiálních systémů.

Abychom mohli vylepšit automatický generátor, prozkoumáme a následně implementujeme některé metody používané v současných nástrojích na řešení soustav polynomiálních rovnic pomocí Gröbnerovýchází. Zaměříme se zejména na algoritmus F_4 představený Jean-Charlesem Faugèrem. Postupy řešení problémů, vygenerované pomocí automatického generátoru, mohou být ještě dále zrychleny, pokud použijeme efektivní metody na práci s řídkými maticemi. Popíšeme a implementujeme metodu, která je založená na rozkladu matic. Tato metoda výrazně urychluje Gauss-Jordanovu eliminaci řídkých matic.

Vylepšení automatického generátoru předvedeme na několika významných minimálních problémech. Ukážeme, že postupy řešení problémů vygenerované novým automatickým generátorem jsou rychlejší a numericky stabilnější než postupy vygenerované původní verzí automatického generátoru.

Klíčová slova: počítačové vidění, robotika, minimální problémy, polynomiální rovnice, Gröbnerovy báze

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List of Symbols and Abbreviations

$C(f), C(F)$	Set of all coefficients of the polynomial f or of all polynomials from the set F .
$\deg(f)$	The total degree of f .
\bar{f}^F	Remainder of the polynomial f on division by F .
gcd	Greatest common multiple.
lcm	Least common divisor.
$LC(f), LC(F)$	Leading coefficient(s) of the polynomial f or of all polynomials from the set F .
$LM(f), LM(F)$	Leading monomial(s) of the polynomial f or of all polynomials from the set F .
$LT(f), LT(F)$	Leading term(s) of the polynomial f or of all polynomials from the set F .
$M(f), M(F)$	Set of all monomials of the polynomial f or of all polynomials from the set F .
$S(f_1, f_2)$	S-polynomial of polynomials f_1 and f_2 .
$T(f), T(F)$	Set of all terms of the polynomial f or of all polynomials from the set F .
$x \mid y$	x divides y .
$\lfloor x \rfloor$	$= \max\{m \in \mathbb{Z} \mid m \leq x\}$; floor function.
\mathbb{Z}_p	Prime field of characteristic p .

1 Introduction

1.1 Motivation

Many problems in computer vision can be formulated using systems of algebraic equations. Examples are the minimal problems [16] which arise when computing geometrical models from image data. The polynomial systems arising from these problems are often not trivial and they consist of many polynomial equations of higher degree in many unknowns and therefore, general algorithms for solving polynomial systems are not efficient for them. So special solvers for each problem have been developed to solve these systems efficiently and numerically robustly.

Minimal problems have a wide range of applications, for example in 3D reconstruction, recognition, robotics and augmented reality. In these applications, the solvers of minimal problems are only small parts of large computation systems which are supposed to be fast or even to work in real-time applications. Moreover, these systems need to compute the solutions of the minimal problems repeatedly for a large number of parameters. Therefore, very efficient solvers are required in computer vision.

Many solvers for minimal problems have been designed ad hoc for concrete problems and therefore, they can not be used or easily modified to solve different or even similar problems. So the automatic generator [12] has been proposed. This tool generates Gröbner basis solvers automatically which enables us to generate an efficient solver for each problem we want to solve.

There are several ways, how the solver using Gröbner basis methods can be generated. The implementation presented in [12] generates polynomials that are required for solving the system systematically. But other methods can be used. In this thesis, we review the state of the art methods for solving polynomial systems and suggest which methods can be taken over to improve the automatic generator and how to implement them.

The automatic generator deals with sparse matrices in most cases. Therefore, we may consider to implement some methods which enable us to work with sparse matrices in a more efficient way to save computation time and memory. In this thesis, we focus on how to improve the Gauss-Jordan elimination of sparse matrices. We use the recent work [11] which presents the significant speed up of Gauss-Jordan elimination of sparse matrices. The speed up is caused by transforming matrices into the singly-bordered block-diagonal forms and by using the partitioning tool PaToH [3]. This method is based on the fact that more eliminations of smaller matrices are faster than one elimination of a big matrix.

1.2 Thesis structure

In this thesis, we firstly review the state of the art methods of computing Gröbner basis of polynomial systems. We start with describing simple, but easily understandable, algorithms and continue with more difficult, but also more efficient, algorithms. It is crucial to us to better understand these algorithms because we will use some techniques from them to improve the automatic generator later in this thesis.

Secondly, we briefly describe the automatic generator. Then, we suggest some improvements of the automatic generator to generate more efficient and numerically stable solvers. Some techniques implemented in the automatic generator may be efficient for some minimal problem, but may be inefficient for another. Therefore, we present a benchmark which enables us to choose the best methods to generate an efficient solver in the end.

Thirdly, we run some experiments to show how the implemented improvements enhanced the automatic generator. We compare the solvers generated with the new automatic generator with the solvers generated by the old implementation.

At last, we conclude by reviewing the contributions of this thesis.

1.3 Notation used

We have decided to use the notation from the [4] in the whole thesis. We just remind that polynomial is a sum of terms and term is a multiple of coefficient and monomial. Be aware that in some literature [1, 6, 7] the meanings of words term and monomial are switched.

2 Polynomial system solving

Firstly we review the state of the art algorithms for computing Gröbner basis. Better understanding of these algorithms helps us to integrate them into polynomial solving algorithms based on Gröbner basis computation more efficiently.

2.1 Buchberger Algorithm

Buchberger Algorithm [2], which was invented by Bruno Buchberger, was the first algorithm for computing Gröbner basis. The algorithm is described in details in [1, 4].

2.1.1 First implementation

The first and easy, but very inefficient implementation of the Buchberger Algorithm, Algorithm 1, is based on the observation that we can extend a set F of polynomials to a Gröbner basis only by adding all non-zero remainders $\overline{S(f_i, f_j)}^F$ of all pairs from F into F until there is no non-zero remainder generated.

The main disadvantage of this simple algorithm is that so constructed Gröbner basis are often bigger than necessary. This implementation of the algorithm is also very inefficient because many of the S-polynomials that are constructed from the critical pairs are reduced to zero so after spending effort on computing them, there is nothing to add to the Gröbner basis G . How to decide which pairs need not be generated is described next.

Algorithm 1 Simple Buchberger Algorithm

Input:

F a finite set of polynomials

Output:

G a finite set of polynomials

```
1:  $G \leftarrow F$ 
2:  $B \leftarrow \{\{g_1, g_2\} \mid g_1, g_2 \in G, g_1 \neq g_2\}$ 
3: while  $B \neq \emptyset$  do
4:   select  $\{g_1, g_2\}$  from  $B$ 
5:    $B \leftarrow B \setminus \{\{g_1, g_2\}\}$ 
6:    $h \leftarrow S(g_1, g_2)$ 
7:    $h_0 \leftarrow \overline{h}^G$ 
8:   if  $h_0 \neq 0$  then
9:      $B \leftarrow B \cup \{\{g, h_0\} \mid g \in G\}$ 
10:     $G \leftarrow G \cup \{h_0\}$ 
11:   end if
12: end while
13: return  $G$ 
```

2.1.2 Improved Buchberger Algorithm

The combinatorial complexity of the simple implementation of the Buchberger Algorithm can be reduced by testing out certain S-polynomials which need not be considered. To know which pairs can be deleted without treatment, we use the first and the second Buchberger's criterion [1]. Sometimes, we can even delete certain polynomials from the set G completely, knowing that every critical pair they will generate will reduce to zero and hence these polynomials themselves will be superfluous in the output set. In the next few paragraphs we will describe the implementation of the Improved Buchberger Algorithm, and of the function *Update*, which deletes the superfluous polynomials from G according to Gebauer and Möller [8].

The Improved Buchberger Algorithm, Algorithm 2, has the same structure as the Simple Algorithm. The function *Update* is used at the beginning of the Improved Buchberger Algorithm to initialize the set B of critical pairs and the Gröbner basis G from the input set F of polynomials and at every moment when a new non-zero polynomial $h_0 = \bar{h}^G$ of an S-polynomial h has been found and the sets B and G are about to be updated.

Algorithm 2 Improved Buchberger Algorithm

Input:
 F a finite set of polynomials

Output:
 G a finite set of polynomials

```

1:  $G \leftarrow \emptyset$ 
2:  $B \leftarrow \emptyset$ 
3: while  $F \neq \emptyset$  do
4:   select  $f$  from  $F$ 
5:    $F \leftarrow F \setminus \{f\}$ 
6:    $(G, B) \leftarrow \text{Update}(G, B, f)$ 
7: end while
8: while  $B \neq \emptyset$  do
9:   select  $\{g_1, g_2\}$  from  $B$ 
10:   $B \leftarrow B \setminus \{\{g_1, g_2\}\}$ 
11:   $h \leftarrow S(g_1, g_2)$ 
12:   $h_0 \leftarrow \bar{h}^G$ 
13:  if  $h_0 \neq 0$  then
14:     $(G, B) \leftarrow \text{Update}(G, B, h_0)$ 
15:  end if
16: end while
17: return  $G$ 

```

Now, let us look at the function *Update*, Algorithm 3. First, it makes pairs from the new polynomial h and all polynomials from the set G_{old} and puts them into the set C . The first while loop (lines 3 – 9) iterates over all pairs in the set C . In each iteration it select a pair $\{h, g_1\}$ from the set C and removes it from the set. Then, it looks for another pair $\{h, g_2\}$ from the set C or the set D . If there is no pair $\{h, g_2\}$ such that (h, g_2, g_1) is a Buchberger triple, then the pair $\{h, g_1\}$ is put into the set D . The triple

(h, g_2, g_1) of polynomials h, g_1 and g_2 is a Buchberger triple if the equivalent conditions

$$\text{LM}(g_2) \mid \text{lcm}(\text{LM}(h), \text{LM}(g_1)) \quad (2.1)$$

$$\text{lcm}(\text{LM}(h), \text{LM}(g_2)) \mid \text{lcm}(\text{LM}(h), \text{LM}(g_1)) \quad (2.2)$$

$$\text{lcm}(\text{LM}(g_2), \text{LM}(g_1)) \mid \text{lcm}(\text{LM}(h), \text{LM}(g_1)) \quad (2.3)$$

are satisfied. From the second Buchberger's criterion, we know that if a Buchberger triple (h, g_2, g_1) shows up in the Buchberger Algorithm and the pairs $\{g_1, g_2\}$ and $\{h, g_2\}$ are amongs the critical pairs, then the pair $\{h, g_1\}$ need not be generated. That means that such a pair is not moved from the set C to the set D but it is only removed from the set C . Moreover, this while loop keeps all pairs $\{h, g_1\}$ where $\text{LM}(h)$ and $\text{LM}(g_1)$ are disjoint, i.e. $\text{LM}(h)$ and $\text{LM}(g_1)$ have no variable in common, even if the pairs could be removed. The reason of this is that if two or more pairs in C have the same lcm of their leading monomials, then there is a choice which one should be deleted. So we keep the pair where the leading monomials are disjoint. Pairs with disjoint leading monomials are removed in the second while loop, so we eventually remove them all.

The second while loop (lines 11 – 17) eliminates all pairs with disjoint leading monomials. We can remove such pairs thanks to the first Buchberger's criterion. All remaining pairs are stored in the set E .

The third while loop (lines 19 – 25) eliminates pairs $\{g_1, g_2\}$ where (g_1, h, g_2) is a Buchberger triple from the set B_{old} . Then the updated set of the old pairs and the new pairs are united into the set B_{new} .

Finally, the last while loop (lines 28 – 34) removes all polynomials g whose leading monomial is a multiple of the leading monomial of h from the set G_{old} . We can eliminate such polynomials for two reasons. Firstly, $\text{LM}(h) \mid \text{LM}(g)$ implies $\text{LM}(h) \mid \text{lcm}(\text{LM}(g), \text{LM}(f))$ for arbitrary polynomial f . We can see that (g, h, f) is a Buchberger triple for any f which in future appears in the set G . Moreover, polynomial g will not be missed at the end because in the Gröbner basis G , polynomials with leading monomials that are multiples of leading monomials of another polynomial from G are superfluous, i.e. they will be eliminated in the reduced Gröbner basis.

In the end of the function, the polynomial h is added into the Gröbner basis G_{new} . The output of the function *Update* is the Gröbner basis G_{new} and the set B_{new} of critical pairs.

2.2 F_4 Algorithm

The F_4 Algorithm [6] by Jean-Charles Faugère is an improved version of the Buchberger's Algorithm. The F_4 replaces the classical polynomial reduction found in the Buchberger's Algorithm by a simultaneous reduction of several polynomials. This reduction mechanism is achieved by a symbolic precomputation followed by Gaussian elimination implemented using sparse linear algebra methods. F_4 speeds up the reduction step by exchanging multiple polynomial divisions for row-reduction of a single matrix.

2.2.1 Improved Algorithm F_4

The main function of the F_4 Algorithm, Algorithm 4, consists of two parts. The goal of the first part is to initialize the whole algorithm.

Algorithm 3 Update

Input:

G_{old} a finite set of polynomials
 B_{old} a finite set of pairs of polynomials
 h a polynomial such that $h \neq 0$

Output:

G_{new} a finite set of polynomials
 B_{new} a finite set of pairs of polynomials

```

1:  $C \leftarrow \{\{h, g\} \mid g \in G_{old}\}$ 
2:  $D \leftarrow \emptyset$ 
3: while  $C \neq \emptyset$  do
4:   select  $\{h, g_1\}$  from  $C$ 
5:    $C \leftarrow C \setminus \{\{h, g_1\}\}$ 
6:   if  $\text{LM}(h)$  and  $\text{LM}(g_1)$  are disjoint or
        $(\text{lcm}(\text{LM}(h), \text{LM}(g_2)) \nmid \text{lcm}(\text{LM}(h), \text{LM}(g_1)) \text{ for all } \{h, g_2\} \in C \text{ and}$ 
        $\text{lcm}(\text{LM}(h), \text{LM}(g_2)) \nmid \text{lcm}(\text{LM}(h), \text{LM}(g_1)) \text{ for all } \{h, g_2\} \in D)$  then
7:      $D \leftarrow D \cup \{\{h, g_1\}\}$ 
8:   end if
9: end while
10:  $E \leftarrow \emptyset$ 
11: while  $D \neq \emptyset$  do
12:   select  $\{h, g\}$  from  $D$ 
13:    $D \leftarrow D \setminus \{\{h, g\}\}$ 
14:   if  $\text{LM}(h)$  and  $\text{LM}(g)$  are not disjoint then
15:      $E \leftarrow E \cup \{\{h, g\}\}$ 
16:   end if
17: end while
18:  $B_{new} \leftarrow \emptyset$ 
19: while  $B_{old} \neq \emptyset$  do
20:   select  $\{g_1, g_2\}$  from  $B_{old}$ 
21:    $B_{old} \leftarrow B_{old} \setminus \{\{g_1, g_2\}\}$ 
22:   if  $\text{LM}(h) \nmid \text{lcm}(\text{LM}(g_1), \text{LM}(g_2))$  or
        $\text{lcm}(\text{LM}(g_1), \text{LM}(h)) = \text{lcm}(\text{LM}(g_1), \text{LM}(g_2))$  or
        $\text{lcm}(\text{LM}(h), \text{LM}(g_2)) = \text{lcm}(\text{LM}(g_1), \text{LM}(g_2))$  then
23:      $B_{new} \leftarrow B_{new} \cup \{\{g_1, g_2\}\}$ 
24:   end if
25: end while
26:  $B_{new} \leftarrow B_{new} \cup E$ 
27:  $G_{new} \leftarrow \emptyset$ 
28: while  $G_{old} \neq \emptyset$  do
29:   select  $g$  from  $G_{old}$ 
30:    $G_{old} \leftarrow G_{old} \setminus \{g\}$ 
31:   if  $\text{LM}(h) \nmid \text{LM}(g)$  then
32:      $G_{new} \leftarrow G_{new} \cup \{g\}$ 
33:   end if
34: end while
35:  $G_{new} \leftarrow G_{new} \cup \{h\}$ 
36: return  $(G_{new}, B_{new})$ 

```

First, it generates the set P of critical pairs and initializes the Gröbner basis G . This is done by taking each polynomial from the input set F and calling the function *Update* on it, which updates the set P of pairs and the set G of basic polynomials.

The second part of the algorithm generates new polynomials and adds them into the set G . In each iteration, it selects some pairs from P using the function *Sel*. Many selection strategies are possible and it is still an open question how to best select the pairs [6]. Some selection strategies are described in the section 2.2.6 on page 12. Then, it splits each selected pair $\{f_1, f_2\}$ into two tuples. The first tuple contains the first polynomial f_1 of the pair and the monomial m_1 such that $\text{LM}(m_1 f_1) = \text{lcm}(\text{LM}(f_1), \text{LM}(f_2))$. The second tuple is constructed in the same way from the second polynomial f_2 of the pair. All tuples from all selected pairs are put into the set L , i.e. duplicates are removed.

Next, function *Reduction* is called on the set L . It stores its result in the set \tilde{F}^+ . In the end of the algorithm it iterates through all new polynomials in the set \tilde{F}^+ and calls the function *Update* on each of them. This generates new pairs into the set P of critical pairs and extends the Gröbner basis G .

This algorithm terminates when the set P of pairs is empty. Then the set G is a Gröbner basis and it is the output of the algorithm.

Algorithm 4 Improved Algorithm F_4

Input:

F a finite set of polynomials

Sel a function $List(Pairs) \rightarrow List(Pairs)$ such that $Sel(l) \neq \emptyset$ if $l \neq \emptyset$

Output:

G a finite set of polynomials

```

1:  $G \leftarrow \emptyset$ 
2:  $P \leftarrow \emptyset$ 
3:  $d \leftarrow 0$ 
4: while  $F \neq \emptyset$  do
5:   select  $f$  form  $F$ 
6:    $F \leftarrow F \setminus \{f\}$ 
7:    $(G, P) \leftarrow Update(G, P, f)$ 
8: end while
9: while  $P \neq \emptyset$  do
10:   $d \leftarrow d + 1$ 
11:   $P_d \leftarrow Sel(P)$ 
12:   $P \leftarrow P \setminus P_d$ 
13:   $L_d \leftarrow Left(P_d) \cup Right(P_d)$ 
14:   $(\tilde{F}_d^+, F_d) \leftarrow Reduction(L_d, G, (F_i)_{i=1, \dots, (d-1)})$ 
15:  for  $h \in \tilde{F}_d^+$  do
16:     $(G, P) \leftarrow Update(G, P, h)$ 
17:  end for
18: end while
19: return  $G$ 

```

2.2.2 Function Update

In the F_4 Algorithm, the standard implementation of the Buchberger's Criteria such as the Gebauer and Möller installation [8] is used. Details about the function *Update* can be found in the section 2.1.2. The pseudocode of the function is shown in Algorithm 3.

2.2.3 Function Reduction

Function *Reduction*, Algorithm 5, performs polynomial division using methods of linear algebra.

The input of the function *Reduction* is a set L containing tuples of monomial and polynomial. These tuples were constructed in the main function of the F_4 Algorithm from all selected pairs.

First, the function *Reduction* calls the function *Symbolic Preprocessing* on the set L . This returns a set F of polynomials to be reduced. To use linear algebra methods to perform polynomial division, the polynomials have to be represented by a matrix. Each column of the matrix corresponds to a monomial. Columns have to be ordered with respect to the monomial ordering used so that the most right column corresponds to "1". Each row of the matrix corresponds to a polynomial from the set F . The matrix is constructed as follows. On the (i, j) position in the matrix, we put the coefficient of the term corresponding to j -th monomial from the i -th polynomial from the set F .

We next reduce the matrix to a row echelon form using, for example, Gauss-Jordan elimination. Note that this matrix is typically sparse so we can use sparse linear algebra methods to save computation time and memory. After elimination, we construct resulting polynomials by multiplying the reduced matrix by a vector of monomials from the right.

In the end, the function returns the set \tilde{F}^+ of reduced polynomials such that their leading monomials are not leading monomials of any polynomial from the set F of polynomials before reduction.

Algorithm 5 Reduction

Input:

- L a finite set of tuples of monomial and polynomial
- G a finite set of polynomials
- $\mathcal{F} = (F_i)_{i=1, \dots, (d-1)}$, where F_i is finite set of polynomials

Output:

- \tilde{F}^+ a finite set of polynomials
- F a finite set of polynomials

- 1: $F \leftarrow \text{Symbolic Preprocessing}(L, G, \mathcal{F})$
 - 2: $\tilde{F} \leftarrow \text{Reduction to a Row Echelon Form of } F$
 - 3: $\tilde{F}^+ \leftarrow \left\{ f \in \tilde{F} \mid \text{LM}(f) \notin \text{LM}(F) \right\}$
 - 4: **return** (\tilde{F}^+, F)
-

2.2.4 Function Symbolic Preprocessing

Function *Symbolic Preprocessing*, Algorithm 6, starts with a set L of tuples, each containing a monomial and a polynomial. These tuples were constructed in the main

function of the F_4 Algorithm from the selected pairs. Then, the tuples are simplified by the function *Simplify* and, after multiplying polynomials with corresponding monomials, the results are put into the set F .

Next, the function goes through all monomials in the set F and for each monomial m looks for some polynomial f from the Gröbner basis G such $m = m' \cdot \text{LM}(f)$ where m' is some monomial. All such polynomials f and monomials m' are, after simplification, multiplied and put into the set F . The goal of this search is to have for every monomial in F a polynomial in F with the same leading monomial. This will ensure that all polynomials from F will be reduced for G after polynomial division by linear algebra.

Algorithm 6 Symbolic Preprocessing

Input:

L a finite set of tuples of monomial and polynomial
 G a finite set of polynomials
 $\mathcal{F} = (F_i)_{i=1, \dots, (d-1)}$, where F_i is finite set of polynomials

Output:

F a finite set of polynomials

```

1:  $F \leftarrow \{\text{multiply}(\text{Simplify}(m, f, \mathcal{F})) \mid (m, f) \in L\}$ 
2:  $\text{Done} \leftarrow \text{LM}(F)$ 
3: while  $\text{M}(F) \neq \text{Done}$  do
4:    $m$  an element of  $\text{M}(F) \setminus \text{Done}$ 
5:    $\text{Done} \leftarrow \text{Done} \cup \{m\}$ 
6:   if  $m$  is top reducible modulo  $G$  then
7:      $m = m' \cdot \text{LM}(f)$  for some  $f \in G$  and some monomial  $m'$ 
8:      $F \leftarrow F \cup \{\text{multiply}(\text{Simplify}(m', f, \mathcal{F}))\}$ 
9:   end if
10: end while
11: return  $F$ 

```

2.2.5 Function Simplify

The function *Simplify*, Algorithm 7, simplifies a polynomial mf which is a product of a given monomial m and a polynomial f .

The function recursively looks for a monomial m' and a polynomial f' such that $\text{LM}(m'f') = \text{LM}(mf)$. The polynomial f' is selected from all polynomials that have been reduced in previous iterations (sets \tilde{F}). We select polynomial f' such that the total degree of m' is minimal.

This is done in the function *Symbolic Preprocessing* to insert polynomials that are mostly reduced and have a small number of monomials into the set F of polynomials to be reduced. This, of course, speeds up the following reduction.

2.2.6 Selection strategy

For the speed of the F_4 Algorithm, it is very important how the critical pairs from the list of all critical pairs P are selected in each iteration. This depends on the implementation of the function *Sel*. There are more possible selection strategies:

- The easiest implementation is to select all pairs from P . In this case we reduce all critical pairs at the same time.

Algorithm 7 Simplify**Input:** m a monomial f a polynomial $\mathcal{F} = (F_i)_{i=1,\dots,(d-1)}$, where F_i is finite set of polynomials**Output:** (m', f') a non evaluated product of a monomial and a polynomial

```

1: for  $u \in$  list of all divisors of  $m$  do
2:   if  $\exists j$  ( $1 \leq j \leq d$ ) such that  $(uf) \in F_j$  then
3:      $\tilde{F}_j$  is the Row Echelon Form of  $F_j$ 
4:     there exists a (unique)  $p \in \tilde{F}_j$  such that  $\text{LM}(p) = \text{LM}(uf)$ 
5:     if  $u \neq m$  then
6:       return  $\text{Simplify}(\frac{m}{u}, p, \mathcal{F})$ 
7:     else
8:       return  $(1, p)$ 
9:     end if
10:  end if
11: end for
12: return  $(m, f)$ 

```

- If the function *Sel* selects only one critical pair then the F_4 Algorithm is the Buchberger Algorithm. In this case the *Sel* function corresponds to the selection strategy in the Buchberger Algorithm.
- The best function that Faugère has tested is to select all critical pairs with a minimal total degree. Faugère calls this strategy the *normal strategy for F_4* . Pseudocode of this function can be found as Algorithm 8.

Algorithm 8 Sel – The normal strategy for F_4 **Input:** P a list of critical pairs**Output:** P_d a list of critical pairs

```

1:  $d \leftarrow \min \{ \deg(\text{lcm}(p)) \mid p \in P \}$ 
2:  $P_d \leftarrow \{ p \in P \mid \deg(\text{lcm}(p)) = d \}$ 
3: return  $P_d$ 

```

2.3 F_5 Algorithm

Since in the Buchberger Algorithm or in the F_4 Algorithm we spend much computation time to compute S-polynomials which will reduce to zero, the F_5 Algorithm [7] by Jean-Charles Faugère was proposed to eliminate these reductions to zero. The F_5 Algorithm saves computation time by removing useless critical pairs which will reduce to zero. The syzygies [4] are used to recognize useless critical pairs in advance.

There are several approaches how to use syzygies to remove useless pairs. For example the idea of [13] is to compute a basis of the module of syzygies together with the

computing of the Gröbner basis of the given polynomial system. Then a critical pair can be removed if the corresponding syzygy is a linear combination of the elements of the basis of syzygies.

The strategy of the F_5 Algorithm is to consider only principal syzygies without computing the basis of the syzygies. The principal syzygy is a syzygy such that $f_i f_j - f_j f_i = 0$ where f_i and f_j are polynomials. This restriction implies that not all useless critical pairs have to be removed so a reduction to zero can still appear later. However it was proved that if the input system is a regular sequence then there is no reduction to zero.

To show how to distinguish which pairs need not be considered, we use the example taken from [7]. Consider polynomials f_1 , f_2 and f_3 . Then, the principal syzygies $f_i f_j - f_j f_i = 0$ can be written as follows:

$$u(f_2 f_1 - f_1 f_2) + v(f_3 f_1 - f_1 f_3) + w(f_2 f_3 - f_3 f_2) = 0 \quad (2.4)$$

where u , v and w are arbitrary polynomials. This can be also rewritten as

$$(u f_2 + v f_3) f_1 - u f_1 f_2 - v f_1 f_3 + w f_2 f_3 - w f_3 f_2 = 0. \quad (2.5)$$

We can see that all relations $h f_1$ are such that h is in the ideal generated by polynomials f_2 and f_3 . So if we have computed Gröbner basis of the polynomials f_2 and f_3 , it is easy to decide which new generated polynomials can be removed. We can remove all polynomials in the form $t f_1$ such that t is a term divisible by leading monomial of an element of the ideal generated by f_2 and f_3 . Therefore the F_5 Algorithm is an incremental algorithm so if we have polynomials f_1, \dots, f_m on the input we have to compute all Gröbner basis of the following ideals: $(f_m), (f_{m-1}, f_m), \dots, (f_1, \dots, f_m)$ in this order.

Many reviews, implementations and modifications of the F_5 Algorithm have been made. Let us emphasize some of them. The first implementation of the F_5 was made by Jean-Charles Faugère himself in the language C. Then there is an implementation in Magma by A. J. M. Segers [17]. Another review and implementation in Magma was done by Till Stegers [18]. Since there is no proof of termination of the F_5 Algorithm, a modification [5] has been introduced such that it always terminates.

3 Automatic generator

The automatic generator of Gröbner basis solvers is used to easily solve problems leading to systems of polynomial equations. These systems usually arise when solving minimal problems [16] in computer vision. Typically, these systems are not trivial so special solvers have to be designed for concrete problems to achieve efficient and numerically stable solvers. But solvers generated for concrete problems can not be easily applied for similar or new problems and therefore the automatic generator was proposed in [12]. Solvers generated by the automatic generator can be easily used to solve complex problems even by non-experts users.

The input of the automatic generator is a system of polynomial equations with a finite number of solutions and the output is a MATLAB or a Maple code that computes solutions of the given system for arbitrary coefficients. One of the goals of this thesis is to improve previous implementation [12] of the automatic generator to construct more efficient and numerically stable solvers.

The newest version of the automatic generator implemented in MATLAB can be downloaded from [15].

3.1 Description of the automatic generator

In this section we would like to briefly describe the procedure for generating solvers. The procedure is based on computation of the action matrix from which solutions can be obtained. The automatic generator consists of several independent modules, see Figure 3.1. Since all these modules are independent, they can be easily improved or replaced by more efficient implementations. Next we describe each of these modules, full description can be found in [12, 10].

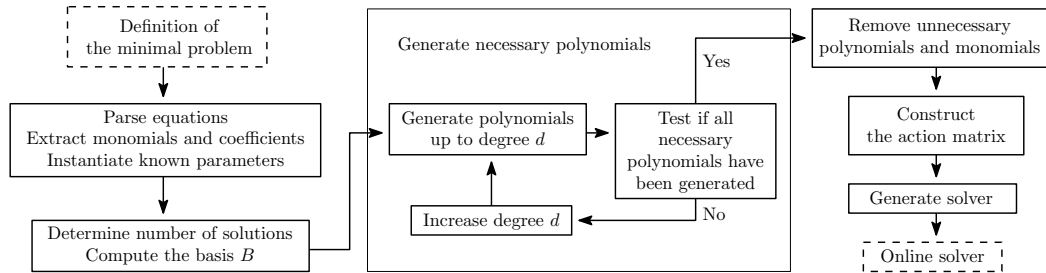


Figure 3.1 Block diagram of the automatic generator

3.1.1 Definition of the minimal problem

Definitions of minimal problems to be solved are given in separate functions that are stored in the folder `minimalProblems`. Each of the definitions has to contain the necessary information about the minimal problem. First of all, the system of polynomial equations with symbolic variables and parameters has to be provided. Next, we have to specify the list of unknown variables and known parameters. Optionally, if we know the monomial basis B of the polynomial system in advance, we can specify it to save

some computation time. The monomial basis B is a set $\{m \mid \overline{m}^G = m\}$ where m is a monomial and G is the Gröbner basis of the given polynomial system. At last we have to set some settings for the automatic generator. We recommend to obtain the default settings by calling the function `gbs.InitConfig()` and only overwrite the settings we want to change. In the folder `minimalProblem`, there are some examples which are self explanatory and can be used as templates to create new minimal problem definitions.

3.1.2 Equations parser, instantiating

In the next step, we have to parse the given equations, which means that we extract monomials and parameters used and obtain total degrees of the polynomials. Then, we instantiate each known parameter with a random number from \mathbb{Z}_p . We assign a unique identifier to each parameter used. The reason is that we need to track the parameters through the process of manipulating with the polynomials in order to be able to restore the process in the solver generation module.

3.1.3 Monomial basis B computation

We need to know the monomials basis B to recognize when we have generated all polynomials that are necessary to build the action matrix. If the basis B was not provided within the definition of the minimal problem, we have to compute it by ourselves. Because there is no function or simple script to compute the basis in MATLAB we have to do it by calling an external software.

The easiest solution to implement was to use the Maple toolbox for MATLAB. This enables us to call Maple functions from the MATLAB environment directly. To use this option we have to set `cfg.GBSolver = @gbs.findAlgB_maple` in the settings of the automatic generator. Unfortunately it shows up that the Maple toolbox for MATLAB is not compatible with the MATLAB Symbolic Math Toolbox in versions newer than R2008 so we do not recommend to use this option nowadays, but the option is still available on older computers.

The second implemented option is to use the algebraic geometry software Macaulay2 [9]. In the folder `gbsMacaulay` there is a template `code_template.m2` into which we simply write the given polynomial system. This updated file is saved as `code.m2` which is executed by Macaulay2 and the results are parsed back in MATLAB. To set up this option we need to install the software Macaulay2 and set `cfg.GBSolver = @gbs.findAlgB_macaulay` in the automatic generator settings. A problem could be that the Macaulay2 is not easy to set up under the Windows OS. Therefore, the installation file of Macaulay2 is provided within the automatic generator. The only thing that has to be done is to edit the file `calc.bat` in the folder `gbsMacaulay` and follow the instructions in the file.

Because of the modularity of the generator, this part can be replaced by another function computing the monomial basis B .

The last option is to compute the basis B in advance and set it into the definition of the minimal problem.

In the end, we have to check the number of solutions of the given polynomial system. If there is a finite number of solutions we can continue with the computation.

3.1.4 Polynomial generator

To be able to build the action matrix, we have to generate enough polynomials such that after their reduction we get polynomials q_i which have leading monomials from

the set $(x_k \cdot B) \setminus B$ where x_k is a variable and all remaining monomials of q_i are from the set B . That is the reason why we had to compute the basis B in the previous step.

In this part of the automatic generator, we represent polynomials as row vectors so that systems of polynomials can be represented by matrices. This representation enables us to easily multiply polynomials with monomials only by shifting the coefficients in the vectors or to reduce the whole polynomial systems by performing the Gauss-Jordan eliminations on the corresponding matrices.

Let $f_i \in F$ where F is a set of polynomials from the input. Let $maxdeg$ is a maximal total degree of all polynomials f_i . At the beginning we put all polynomials $\{mf_i \mid f_i \in F; \deg(mf_i) = \deg(f_i), \dots, maxdeg\}$ into the matrix M , where m is a monomial. Now we perform the Gauss-Jordan elimination on the matrix M and save the result as matrix \tilde{M} . Then we check if there exists a variable x_k for which all required polynomials q_i are present in \tilde{M} . If we find such a variable we can continue with the construction of the action matrix for the variable. If not, we have to add more polynomials to the matrix M . We increment $maxdeg$ by one and add all polynomials $\{mf_i \mid f_i \in F; \deg(mf_i) = maxdeg\}$ to the matrix M . Then we continue with the elimination and with the checking the action matrix requirements as explained above. We repeat these steps until all required polynomials q_i are generated so the action matrix can be built. The pseudocode of this process is shown in Algorithm 9. The function *Check Action Matrix Conditions* from this code checks if all polynomials q_i are generated in \tilde{M} for at least one variable from the given list of variables. If such a variable is found, the function returns it, otherwise it returns an empty set.

Algorithm 9 Polynomial generator – One elimination solver

Input:

F a set of polynomials
 $variables$ a list of variables
 $algB$ a monomial basis B

Output:

\tilde{M} a matrix representing a set of polynomials
 var a variable

```

1:  $maxdeg \leftarrow \max\{\deg(f_i) \mid f_i \in F\}$ 
2:  $M \leftarrow \{mf_i \mid f_i \in F; \deg(mf_i) = \deg(f_i), \dots, maxdeg; m \text{ is a monomial}\}$ 
3:  $\tilde{M} \leftarrow$  Reduction to a Row Echelon Form of  $M$ 
4:  $var \leftarrow \text{Check Action Matrix Conditions}(\tilde{M}, variables, algB)$ 
5: while  $var = \emptyset$  do
6:    $maxdeg \leftarrow maxdeg + 1$ 
7:    $M \leftarrow M \cup \{mf_i \mid f_i \in F; \deg(mf_i) = maxdeg; m \text{ is a monomial}\}$ 
8:    $\tilde{M} \leftarrow$  Reduction to a Row Echelon Form of  $M$ 
9:    $var \leftarrow \text{Check Action Matrix Conditions}(\tilde{M}, variables, algB)$ 
10: end while
11: return  $(\tilde{M}, var)$ 

```

In this whole process we need to keep track how the matrix M was built. Recall that each coefficient of the polynomials f_i has a unique identifier assigned to it in the equations parser. Because the whole matrix M contains only the polynomials f_i or their multiples with monomials, only the coefficients from the polynomials f_i appear in the matrix M . We just have to keep the positions of the coefficients. This is done by matrix \hat{M} . The matrix \hat{M} is built at the same time as the matrix M by this way. When

we put a coefficient into the matrix M , we also put the corresponding identifier to the matrix \hat{M} at the same position. The matrix \hat{M} enables us to recover the process of polynomial generation in the code generator module.

3.1.5 Removing unnecessary polynomials and monomials

Since the polynomials were generated systematically in the previous step there may appear some polynomials which are not necessary for the constructing of the action matrix. The goal of this part of the automatic generator is to remove as many as possible polynomials which are not necessary.

We can remove a polynomial r from the matrix M if the corresponding eliminated matrix \tilde{M} still contains all required polynomials q_i . In this way we try to remove all polynomials from M .

Because the success of removing a polynomial depends on the previous removals, the number of removed polynomials depends on the ordering in which the polynomials are removed. In the automatic generator we start removing polynomials from the one with the largest leading monomial by monomial ordering used. Because it is very inefficient to remove polynomials one by one and perform each time an expensive Gauss-Jordan elimination, we can enhance the procedure by trying to remove more polynomials at the time. In the automatic generator, this heuristic is used. If we have successfully removed k polynomials, we try to remove $2k$ polynomials in the next step. If the removal of k polynomials have failed, we try to remove $\frac{1}{4}k$ polynomials in the next step. The pseudocode of this removing process is shown as Algorithm 10.

Moreover we can reduce the size of the matrix M by removing unnecessary monomials. A monomial is unnecessary when its removal does not affect the building of the action matrix. We have to keep all monomials such that they are leading monomials of polynomials in the corresponding matrix \tilde{M} and all monomials that are present in the basis B . All other monomials can be removed. If we remove all such unnecessary monomials then the matrix M will have dimensions $n \times (n + N)$ where n is the number of the polynomials in the matrix M and N is the number of solutions of the given system.

3.1.6 Construction of the action matrix

This part of the automatic generator starts with the eliminated matrix \tilde{M} of polynomials and variable x_k for which all required polynomials q_i are present in \tilde{M} .

Let us describe the construction of the action matrix in an informal and practical way rather than by using the theory. If the theory is needed, it can be found in [10]. The action matrix M_{x_k} corresponding to the variable x_k is a square matrix of dimensions $N \times N$ where N is the number of elements of the monomial basis B . Each row and column of M_{x_k} corresponds to a monomial $b_i \in B$. Let the monomials b_i be sorted such that if $b_l \prec b_k$ then $k < l$ where \prec is the monomial ordering used. We put coefficients of the polynomial $m_i = \overline{(x_k b_i)}^F$ to the i -th row where F are polynomials corresponding to \tilde{M} . Because \tilde{M} is in a row echelon form there are two possibilities how the i -th row can be constructed:

1. $x_k b_i = b_j$ for some $b_j \in B$.

That means that $x_k b_i$ is irreducible by F and m_i is a monomial in B . In this case we set $M_{x_k}(i, j) = 1$ and $M_{x_k}(i, k) = 0$ where $k \neq j$.

2. $x_k b_i \neq b_j$ for all $b_j \in B$.

Algorithm 10 Remove unnecessary polynomials**Input:** M a matrix representing a set of polynomials $variable$ a variable $algB$ a monomial basis B **Output:** M a matrix representing a set of polynomials

```

1:  $rows \leftarrow$  number of rows of  $M$ 
2:  $step \leftarrow \max\{\lfloor rows/32 \rfloor, 1\}$ 
3:  $up \leftarrow 1$ 
4:  $filter \leftarrow \{1, 2, \dots, rows\}$ 
5: while  $up \leq rows$  do
6:    $down \leftarrow up + step - 1$ 
7:   if  $down > rows$  then
8:      $down \leftarrow rows$ 
9:      $step \leftarrow down - up + 1$ 
10:  end if
11:   $filter_{old} \leftarrow filter$ 
12:   $filter \leftarrow filter \setminus \{up, up + 1, \dots, down\}$ 
13:   $\tilde{M} \leftarrow$  Reduction to a Row Echelon Form of  $M$  only with rows specified by  $filter$ 
14:   $v \leftarrow Check\ Action\ Matrix\ Conditions(\tilde{M}, variable, algB)$ 
15:  if  $v = variable$  then
16:     $up \leftarrow down + 1$ 
17:     $step \leftarrow 2step$ 
18:  else
19:    if  $step = 1$  then
20:       $up \leftarrow up + 1$ 
21:    else
22:       $step \leftarrow \max\{\lfloor step/4 \rfloor, 1\}$ 
23:    end if
24:     $filter \leftarrow filter_{old}$ 
25:  end if
26: end while
27: return  $M$  only with rows specified by  $filter$ 

```

In this case there is f such that $LM(m_i) = LM(f)$ where $f \in F$ so $m_i = x_k b_i - f$. Since all monomials of f except $LM(f)$ are from B , all monomials of m_i are also from B . We put coefficient of m_i at the monomial b_j to the matrix M_{x_k} on the (i, j) position.

Now, the solutions of the given system can be easily found by computing right eigenvectors of the action matrix M_{x_k} .

3.1.7 Solver generator

The last task of the automatic generator is to create a solver which will solve the given polynomial system for an arbitrary set of parameters preserving its structure. The current version of the automatic generator can generate solvers for MATLAB and Maple but new code generators can be easily added. It can be set in the min-

3 Automatic generator

imal problem definition by setting `cfg.exportCode` which solvers will be generated. For instance to create both MATLAB and Maple solvers we set `cfg.exportCode = {'matlab' 'maple'}`.

To create a solver we have to restore the process of creation of the matrix M . This process is saved as the matrix \hat{M} which contains unique identifiers on the positions where the given parameters have to be put. So the matrix M can be built for each given set of parameters. Then the Gauss-Jordan elimination is called on M so we get the matrix \tilde{M} . Now the action matrix is built in the same way as above and the solutions are extracted from it. To sum up the final solver just creates the matrix M by putting parameters to the correct places. After Gauss-Jordan elimination the action matrix is built by copying some parts of rows of \tilde{M} and then the solutions are extracted by using the eigenvectors of the action matrix.

3.1.8 Usage

The automatic generator is designed to be used even by non-expert users and to be easily expanded or improved.

At first, the script `setpaths.m` should be executed from the root directory of the automatic generator. This will add all required paths to the MATLAB environment.

Next we have to set up the definition of the minimal problem we want to solve. How the definition have to be specified is written in the section 3.1.1. All these definitions are stored in the folder `minimalProblems`. To generate the solver we call the function `gbs.GenerateSolver(MinimalProblem)` where `MinimalProblem` is the name of the definition of the minimal problem, i.e. the name of the function in the folder `minimalProblems`. This will generate us solvers `solver_MinimalProblem.m` for the MATLAB solver and `solver_MinimalProblem.txt` for the Maple solver. These solvers are stored in the folder `solvers`.

For example, let us present generating of a solver for the 6-point focal length problem [14]. We have defined this problem as a function `sw6pt.m` in the folder `minimalProblems`. By calling the function `gbs.GenerateSolver('sw6pt')` we get solvers `solver_sw6pt.m` and `solver_sw6pt.txt` in the folder `solvers`.

3.2 Improvements

The bottleneck of the automatic generator is the polynomial generator module. Since the polynomials are generated systematically, the matrices in the resultant solvers are often bigger than necessary which means that the solvers are not efficient. So many improvements of the automatic generator [12] can be done. For example, if we want to generate multiple elimination solvers as suggested in [10], the polynomial generator module have to be improved or totally replaced. In the same way some strategies from other algorithms, for example from the F_4 Algorithm [6], can be taken over and implemented into the automatic generator. Because we are mostly working with sparse matrices in the automatic generator, the variant of Gauss-Jordan elimination for sparse matrices can be implemented to save some computation time.

3.2.1 Reimplementation

The previous implementation [12] of the automatic generator was implemented in MATLAB R2008. It shows up that new versions of MATLAB are not backward compatible so the automatic generator fails when launched in some newer version than R2008.

So the first task was to reimplement the old implementation into new version of MATLAB. All changes of the code were minor and just in the implementation level.

One important change is that the Maple Toolbox for MATLAB is not compatible with the MATLAB Symbolic Math Toolbox. One of the options in the monomials basis B module is to use the Maple toolbox to compute the basis B . Because of the incompatibility, this option can be used no longer and the algebraic geometry software Macaulay2 [9] have to be used.

The new version of the automatic generator, as it is described in this thesis, is compatible with the version R2015 of MATLAB 64-bit and 32-bit under Windows and Unix operation systems.

3.2.2 Multiple elimination solver

In the section 3.1.4, there is described the strategy how to generate polynomials for one elimination solvers. But it may be better to create multiple elimination solvers in some cases. A multiple elimination solver is a solver where polynomials are generated systematically by multiplying already generated polynomials by monomials and reduced each time by Gauss-Jordan elimination. So the task of this section is to describe how the polynomial generator of the automatic generator can be improved to be able to generate polynomials for multiple elimination solvers.

In this strategy, we generate in each step all polynomials up to degree d and perform a Gauss-Jordan elimination on them. We increase the degree d when no new polynomials can be generated by multiplying already generated polynomials by some monomials. We stop this process when all polynomials q_i are generated.

This strategy is very useful especially when we are generating solvers for systems with many variables. The reason is that the increasing of the degree d of generated polynomials leads to a large number of new generated polynomials.

Now, let us look on the process of generating polynomials in more details. The pseudocode is shown as Algorithm 11. Let the *maxdeg* is a maximal total degree of all polynomials from the given system F . At the beginning, we put into the matrix M_1 all polynomials up to degree *maxdeg* such that they are multiples of polynomials from F and some monomials. We get the matrix \tilde{M}_1 by eliminating the matrix M_1 . We check if there exists a variable for which all polynomials q_i are generated in \tilde{M}_1 . If no such variable is found, we generate new polynomials with higher total degree. We increase the degree *maxdeg* up to which we are generating polynomials. The variable *step* tells how much we want to increase the total degree in one step. Into the variable *mindeg* we save the *maxdeg* from the previous iteration incremented by one to keep track to which degree we have generated polynomials yet. We get new matrix M_2 by copying the matrix \tilde{M}_1 and we add all polynomials with total degrees from *mindeg* to *maxdeg* to M_2 . These polynomials are multiples of polynomials from \tilde{M}_1 and some monomials. We save the result of the Gauss-Jordan elimination as the matrix \tilde{M}_2 . We repeat this process until no new polynomials are added in one iteration. That situation happens when two matrices \tilde{M}_j and \tilde{M}_{j-1} have the same number of non zero rows. In this case we check if all polynomials q_i are generated for some variable. If not, we have to generate new polynomials with higher total degree. If the variable has been found, we return the last generated matrix \tilde{M}_j and the variable. You may notice that when we are leaving the repeat-until loop on line 13, there are two equivalent matrices \tilde{M}_j and \tilde{M}_{j-1} . These matrices have the same non zero rows and differ only with the number of zero rows. This is the reason why we can remove the matrix \tilde{M}_j by decrementing the variable j on line 14.

Algorithm 11 Polynomial generator – Multiple elimination solver**Input:**

F a set of polynomials
 $variables$ a list of variables
 $algB$ a monomial basis B
 $step$ an integer

Output:

\tilde{M} a matrix representing a set of polynomials
 var a variable

```

1:  $maxdeg \leftarrow \max\{\deg(f_i) \mid f_i \in F\}$ 
2:  $j \leftarrow 1$ 
3:  $\tilde{M}_1 \leftarrow \{mf_i \mid f_i \in F; \deg(mf_i) = \deg(f_i), \dots, maxdeg; m \text{ is a monomial}\}$ 
4:  $\tilde{M}_1 \leftarrow \text{Reduction to a Row Echelon Form of } \tilde{M}_1$ 
5:  $var \leftarrow \text{Check Action Matrix Conditions}(\tilde{M}_1, variables, algB)$ 
6: while  $var = \emptyset$  do
7:    $mindeg \leftarrow maxdeg + 1$ 
8:    $maxdeg \leftarrow maxdeg + step$ 
9:   repeat
10:     $j \leftarrow j + 1$ 
11:     $M_j \leftarrow \tilde{M}_{j-1} \cup \left\{ mf_i \mid f_i \in \tilde{M}_{j-1}; \right.$ 
       $\left. \deg(m \times f_i) = mindeg, \dots, maxdeg; m \text{ is a monomial} \right\}$ 
12:     $\tilde{M}_j \leftarrow \text{Reduction to a Row Echelon Form of } M_j$ 
13:    until number of nonzero rows of  $\tilde{M}_j = \text{number of nonzero rows of } \tilde{M}_{j-1}$ 
14:     $j \leftarrow j - 1$ 
15:     $var \leftarrow \text{Check Action Matrix Conditions}(\tilde{M}_j, variables, algB)$ 
16: end while
17: return  $(\tilde{M}_j, var)$ 

```

We have to keep track how the matrices M_j were built to be able to restore the process of generation of polynomials and generate the code of the solver in the solver generator module. Therefore, we build a matrix \hat{M}_j for each matrix M_j . The first matrix \hat{M}_1 is built in the same way as the matrix \hat{M} when generating one elimination solver. This matrix contains only the unique identifiers of parameters on positions where real values will be put. Because each matrix M_j is built from the matrix \tilde{M}_{j-1} the matrix M_j contains only coefficients from the matrix \tilde{M}_{j-1} . So when a coefficient from (m, n) position from \tilde{M}_{j-1} is put into M_j at (k, l) position, the tuple (m, n) is put at the position (k, l) of \hat{M}_j . So if we have the matrix \tilde{M}_{j-1} and the matrix \hat{M}_j , the matrix M_j can be built easily.

To enable generation of multiple elimination solvers, we assign an integer to `cfg.PolynomialsGeneratorCfg.GJstep` in the settings of the automatic generator. The value of the `GJstep` has the same meaning as the variable *step* from the Algorithm 11. E.g. by setting `GJstep = 1` the generated polynomials will be eliminated each time the total degree of generated polynomials is incremented by 1. If we set `GJstep = 0`, the one elimination solver will be generated as written in the section 3.1.4.

3.2.3 Removing redundant polynomials

We may notice that there appear matrices \tilde{M}_j with many zero rows in the process of generation polynomials for multiple elimination solvers. This is caused because there are many dependent rows in the corresponding matrices M_j . These zero rows in matrices \tilde{M}_j give us no new information so we want to remove as many as possible rows from the matrices M_j such that the resulting matrices \tilde{M}_j will have the same nonzero rows as before the removal and will have no zero rows.

We know that we can remove the same number of rows from M_j as it is the number of zero rows in \tilde{M}_j . But we do not know which rows we should remove. So we try to remove each row r from M_j and if the number of nonzero rows of \tilde{M}_j stays the same, the removal is successful, if not, we have to return the row r back into M_j . We end this process of removal when there is no zero row in the matrix \tilde{M}_j . Because performing the Gauss-Jordan elimination in each step of removing single row is inefficient we use the same heuristic as described in the section 3.1.5. For better understanding we are providing the pseudocode of this removing as Algorithm 12.

Because this removing process removes only zero rows from the matrices \tilde{M}_j and no others rows are touched it does not influences the process of adding polynomials. Therefore, this removing process is enabled by default and can not be disabled by any option in the automatic generator settings.

3.2.4 Matrix partitioning

In the automatic generator, we are dealing with matrices that are mostly sparse, so some more efficient techniques can be used to work with them. This will of course result into generation of more efficient and numerically stable solvers.

In this section, we focus on how to speed up the Gauss-Jordan elimination of sparse matrices. We use the technique proposed in [11]. We observe that by permuting the rows and the columns of sparse matrices they can be transformed into matrices with block-diagonal structure known as singly-bordered block-diagonal (SBBD) form. Each diagonal block of the SBBD matrices forms an independent problem and therefore, it can be independently eliminated. This speeds up the process of Gauss-Jordan elimination because eliminating more smaller matrices is faster than eliminating one big matrix. If we divide the matrix into k independent blocks that contain comparable number of entries, the speed up is approximately $n^3 \rightarrow k \cdot \left(\frac{n}{k}\right)^3$. Moreover, the permutation matrices that transform matrices to the SBBD forms are precomputed during the solver generation process and therefore, the resultant solver is working already with matrices in the SBBD forms and does not have to spend time to computing the permutation matrices again.

Let us say we want to eliminate matrix M . First of all, we have remove columns that correspond to monomials from the basis B from the matrix because these columns should not be permuted and eliminated. Then, we need to compute the permutation matrix. To compute the permutation matrices, we use the state of the art hypergraph partitioning tool PaToH [3] with settings to divide the matrix into two independent blocks. We do the permutations of rows a columns and get two diagonal blocks M_{11} and M_{22} and coupling columns that can not be assigned to any of the diagonal blocks. Next, we perform two independent eliminations of the blocks M_{11} and M_{22} and permute all rows of M to get the identity matrix in the left top corner. However, we get non-eliminated submatrix in the right bottom corner of M . After eliminating this submatrix, the rows above this submatrix are still not eliminated. If this is the last elimination

Algorithm 12 Remove redundant polynomials**Input:** M a matrix representing a set of polynomials \tilde{M} a matrix in a Row Echelon Form representing a set of polynomials**Output:** M a matrix representing a set of polynomials \tilde{M} a matrix in a Row Echelon Form representing a set of polynomials

```

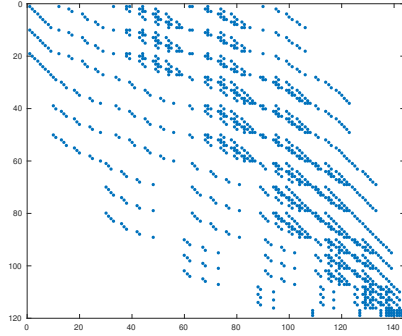
1:  $toRemove \leftarrow$  number of zero rows of  $\tilde{M}$ 
2:  $nonZero \leftarrow$  number of non zero rows of  $\tilde{M}$ 
3:  $rows \leftarrow$  number of rows of  $M$ 
4:  $step \leftarrow \max\{\lfloor toRemove/4 \rfloor, 1\}$ 
5:  $up \leftarrow 1$ 
6:  $filter \leftarrow \{1, 2, \dots, rows\}$ 
7: while  $toRemove \neq 0$  do
8:    $down \leftarrow up + step - 1$ 
9:   if  $down > rows$  then
10:     $down \leftarrow rows$ 
11:     $step \leftarrow down - up + 1$ 
12:   end if
13:    $filter_{Old} \leftarrow filter$ 
14:    $filter \leftarrow filter \setminus \{up, up + 1, \dots, down\}$ 
15:    $\tilde{M} \leftarrow$  Reduction to a Row Echelon Form of  $M$  only with rows specified by  $filter$ 
16:   if number of non zero rows of  $\tilde{M} < nonZero$  then
17:     if  $step = 1$  then
18:        $up \leftarrow up + 1$ 
19:     else
20:        $step \leftarrow \max\{\lfloor step/4 \rfloor, 1\}$ 
21:     end if
22:      $filter \leftarrow filter_{Old}$ 
23:   else
24:      $toRemove \leftarrow$  number of zero rows of  $\tilde{M}$ 
25:      $up \leftarrow down + 1$ 
26:      $step \leftarrow \min\{2step, toRemove\}$ 
27:   end if
28: end while
29: return ( $M$  only with rows specified by  $filter$ ,  $\tilde{M}$ )

```

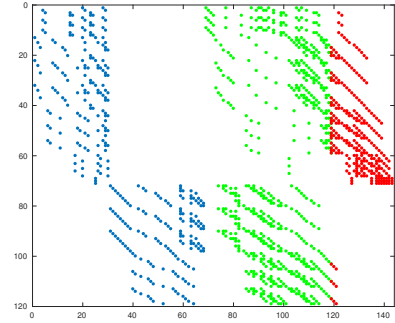
in the solver, we have to eliminate only the rows which we need to build the action matrix. If this is not the last elimination in the solver, we have to eliminate them all.

Example Consider sparse matrix M of size 119×143 as it is shown in Figure 3.2a. Columns 119 – 143 correspond to monomials from the monomial basis B . When we remove these columns, we get rectangular matrix of size 119×119 on which we execute the partitioning tool PaToH. After the permutation of the rows and columns, we get the matrix in the SBBB form which can be seen in Figure 3.2b. We get two diagonal blocks M_{11} of size 71×30 and M_{22} of size 48×38 and 51 coupling columns which can not be assigned to any diagonal block. After two independent Gauss-Jordan eliminations of the blocks M_{11} and M_{22} and row permutation, we get the identity matrix in the left

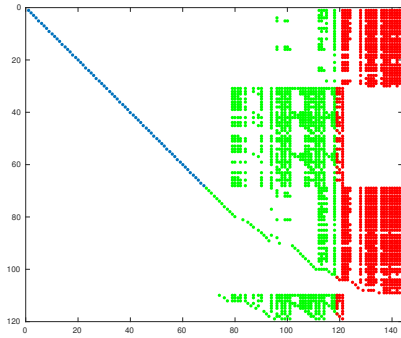
top corner, see Figure 3.2c. Now, we have to perform the Gauss-Jordan elimination on submatrix of size 51×75 in the right bottom corner. After this, we get matrix as it is shown in Figure 3.2d. Now, uneliminated submatrix of size 68×75 left in the right top corner of the matrix. If this is the last elimination in the solver, we do not have to eliminate it whole, but it is sufficient to eliminate only the rows we need to the constructing of the action matrix. If this is not the last elimination in the solver, we have to eliminate the whole remaining uneliminated submatrix.



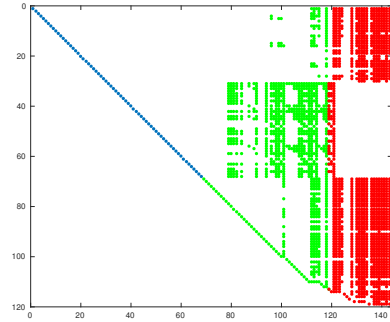
(a) The input matrix



(b) The SSBD form of this matrix



(c) A matrix obtained after two independent Gauss-Jordan eliminations



(d) A matrix obtained after elimination of the right bottom submatrix

Figure 3.2 Example of the process of eliminating matrix using matrix partitioning. Colors: blue – two independent diagonal blocks, green – coupling columns, red – columns corresponding to the basis B

Since matrix partitioning have not to be efficient for all minimal problems, it can be easily enabled or disabled in the automatic generator. By setting `cfg.matrixPartitioning = 'all'` matrix partitioning is used to all Gauss-Jordan eliminations in the solver. If `cfg.matrixPartitioning = 'last'` is set, matrix partitioning is used only to the last Gauss-Jordan elimination in the solver. Matrix partitioning can be totally disabled by setting `cfg.matrixPartitioning = 'none'`. At last, we want to warn that the tool PaToH is not available under Windows OS so the matrix partitioning can not be used under this system.

3.2.5 F4 strategy

Because polynomials are generated systematically in the polynomial generator module as it is described in section 3.1.4, many of them are superfluous and therefore, need not be generated. Since the automatic generator consists of independent modules, we can replace the polynomial generator module by some better implementation.

We have described some of the state of the art techniques how polynomial systems can be solved in the chapter 2. Therefore, we can take over some of them and implement them into the automatic generator. In the section 2.2, we have understood the F_4 [6] Algorithm so we have implemented this technique into the automatic generator.

Implementation of the F_4 Algorithm in the automatic generator is the same as J. Ch. Faugère has described in [6] and we did in section 2.2. The only difference is that we need to track how the polynomials are constructing to be able to reconstruct the process in the solver generator module. In the F_4 Algorithm, to be concrete in the function *Symbolic Preprocessing*, we are constructing matrices F_i from the selected pairs and polynomials from Gröbner basis G that are multiplied by a monomial. Polynomials that are constructed from the selected critical pairs are from G and multiplied by a monomial too. But polynomials in G are just the input polynomials or polynomials from \tilde{F}_i from all previous iterations. All these polynomials that are added into F_i are simplified by the function *Simplify*. That means that such a polynomial may be replaced by another polynomial taken from \tilde{F}_i . To sum up, the matrix F_i is built from multiples of the input polynomials or polynomials from $\tilde{F}_{1,\dots,i-1}$ and monomials. So to track the process of building the matrices F_i , we just have to keep which polynomials from which matrices \tilde{F}_i (we can look at the input polynomials as if it is a matrix \tilde{F}_0) multiplied with which monomials are used. In the end, we have to recover how the matrix G was built, but this is the same case as reconstructing a matrix F_i because the Gröbner basis G consists only of the input polynomials or polynomials from matrices \tilde{F}_i .

Unnecessary and redundant polynomials can be, of course, removed from the matrices F_i as we have described in sections 3.1.5 and 3.2.3. Moreover, if nothing is added from the matrix \tilde{F}_i to the Gröbner basis G , i.e. the matrix \tilde{F}_i^+ is empty, the matrix F_i can be removed totally. This leads to that in the resultant generated solver, there will be no reduction to zero so much computation time can be saved. We are still working with sparse matrices so the matrix partitioning which is described in section 3.2.4 can be used to speed up the Gauss-Jordan eliminations.

By default, this strategy is disabled in the automatic generator and the systematic polynomial generator as described in sections 3.1.4 and 3.2.2 is used. This is done by setting `cfg.PolynomialsGenerator = 'systematic'`. To enable the polynomial generator using the F_4 strategy, set `cfg.PolynomialsGenerator = 'F4'` in the automatic generator settings.

The key function in the F_4 strategy is the *Sel* function which is described in section 2.2.6. While different *Sel* functions can be efficient for different minimal problems, it can be easily changed which function will be used. To use the normal strategy, set `cfg.PolynomialsGeneratorCfg.Sel = @F4_SelNormal` and to select only one critical pair each time, set `cfg.PolynomialsGeneratorCfg.Sel = @F4_SelFirst` in the automatic generator settings. This second function emulates the Buchberger Algorithm. Both this functions are stored in the folder `generator/F4` and everybody can implement and use his own *Sel* function.

3.3 Benchmark

4 Experiments

5 Conclusion

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