

Quantifier Elimination by Cylindrical Algebraic Decomposition Based on Regular Chains

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ABSTRACT

A quantifier elimination algorithm by cylindrical algebraic decomposition based on regular chains is presented. The main idea is to refine a complex cylindrical tree until the signs of polynomials appearing in the tree are sufficient to distinguish the true and false cells. We report on an implementation of our algorithm in the *RegularChains* library in MAPLE and illustrate its effectiveness by examples.

Categories and Subject Descriptors

I.1.2 [Symbolic and Algebraic Manipulation]: Algorithms—Algebraic algorithms, Analysis of algorithms

General Terms

Algorithms, Experimentation, Theory

Keywords

quantifier elimination, cylindrical algebraic decomposition, regular chains, triangular decomposition

1. INTRODUCTION

Quantifier elimination over real closed fields (QE) has been applied successfully to many areas in mathematical sciences and engineering. The following textbooks and journal special issues [18, 12, 6, 3] demonstrate that QE is one of the major applications of symbolic computation.

It is well known that the worst-case running time for real quantifier elimination is doubly exponential in the number of variables of the input formula, even if there is only one free variable and all polynomials in the quantified input are linear, see the paper [5]. It is also well-known that QE based on Cylindrical Algebraic Decomposition (CAD) has a worst-case doubly exponential running time, even when the number of quantifier alternations is constant, meanwhile other QE algorithms are only doubly exponential in the number

of quantifier alternations [20, 2]. Despite of these theoretical results, the practical efficiency and the range of the applications of CAD-based QE have kept improving regularly since Collins' landmark paper [10]. Today, CAD-based QE is available to scientists and engineers thanks to different software namely QEPCAD¹, Mathematics², REDLOG³, SYNRAc⁴, *RegularChains*⁵.

In [9], together with B. Xia and L. Yang, we presented a different way of computing CADs, based on triangular decomposition of polynomial systems. Our scheme relies on the concept of *cylindrical decomposition of the complex space* (CCD), from which a CAD can be easily derived. Since regular chains theory is at the center of this new scheme, we call it RC-CAD. Meanwhile, we shall denote by PL-CAD Collins' projection-lifting scheme for CAD construction.

In [8], we substantially improved the practical efficiency of the RC-CAD scheme by means of an incremental algorithm for computing CADs; an implementation of this new algorithm, realized within the *RegularChains* library, outperforms PL-CAD-based solvers on many examples taken from the literature.

The purpose of the present paper is to show that RC-CAD, supported by this incremental algorithm, can serve the purpose of real QE. In addition, our implementation of RC-CAD-based QE is competitive with software implementing PL-CAD-based QE.

We turn our attention to the theoretical implication of performing QE by RC-CAD. If extended Tarski formulae are allowed, then deriving QE from a RC-CAD is a straightforward procedure, hence, we shall not discuss it here. In the rest of this paper, for both input and output of QE problems, only polynomial constraints (with rational number coefficients) will be allowed, thus excluding the use of algebraic expressions containing radicals.

In Collins' original work, the augmented projection operator was introduced in order to find a sufficiently large set of polynomials such that their signs alone could distinguish true and false cells. In [17], Hong produced simple solution formula constructions, assuming that the available polynomials in a CAD are sufficient to generate output formulae.

In his PhD thesis [4], Brown then introduced ways to add

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¹QEPCAD: <http://www.usna.edu/CS/~qepcad/B/QEPCAD.html>

²Mathematics: <http://www.wolfram.com/mathematica/>

³REDLOG: <http://www.redlog.eu/>

⁴SYNRAc: <http://jp.fujitsu.com/group/labs/techinfo/freesware/synrac/>

⁵RegularChains: <http://www.regularchains.org/>

Quantifier Elimination And Cylindrical Algebraic Decomposition

**François Boulier, Matthew
England, Timur M. Sadykov, Evgenii V.
Vorozhtsov**

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Quantifier Elimination and Cylindrical Algebraic Decomposition Bob F. Caviness, Jeremy R. Johnson, 2012-12-06 George Collins discovery of Cylindrical Algebraic Decomposition CAD as a method for Quantifier Elimination QE for the elementary theory of real closed fields brought a major breakthrough in automating mathematics with recent important applications in high tech areas e g robot motion also stimulating fundamental research in computer algebra over the past three decades This volume is a state of the art collection of important papers on CAD and QE and on the related area of algorithmic aspects of real geometry It contains papers from a symposium held in Linz in 1993 reprints of seminal papers from the area including Tarski s landmark paper as well as a survey outlining the developments in CAD based QE that have taken place in the last twenty years **Computer Algebra in Scientific Computing** François Boulrier, Matthew England, Timur M. Sadykov, Evgenii V. Vorozhtsov, 2020-10-17 This book constitutes the refereed proceedings of the 22nd International Workshop on Computer Algebra in Scientific Computing CASC 2020 held in Linz Austria in September 2020 The conference was held virtually due to the COVID 19 pandemic The 34 full papers presented together with 2 invited talks were carefully reviewed and selected from 41 submissions They deal with cutting edge research in all major disciplines of computer algebra The papers cover topics such as polynomial algebra symbolic and symbolic numerical computation applications of symbolic computation for investigating and solving ordinary differential equations applications of CAS in the investigation and solution of celestial mechanics problems and in mechanics physics and robotics *Formal Methods* André Platzer, Kristin Yvonne Rozier, Matteo Pradella, Matteo Rossi, 2024-09-10 The open access book set LNCS 14933 14934 constitutes the refereed proceedings of the 26th International Symposium on Formal Methods FM 2024 which took place in Milan Italy in September 2024 The 51 full and 4 short papers included in these proceedings were carefully reviewed and selected from 219 submissions They also include 2 invited talks in full paper length and 10 tutorial papers The contributions were organized in topical sections as follows Part I Invited papers fundamentals of formal verification foundations learn and repair programming languages logic and automata Part II Tools and case studies embedded systems track industry day track tutorial papers *Automated Deduction in Geometry* Francisco Botana, Pedro Quaresma, 2015-07-17 This book constitutes the thoroughly refereed post workshop proceedings of the 10th International Workshop on Automated Deduction in Geometry ADG 2014 held in Coimbra Portugal in July 2014 The 11 revised full papers presented in this volume were carefully selected from 20 submissions The papers show the trend set of current research in automated reasoning in geometry

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were carefully reviewed and selected from 39 submissions They deal with cutting edge research in all major disciplines of Computer Algebra

Artificial Intelligence and Symbolic Computation Jaques Calmet,Tetsuo Ida,Dongming Wang,2006-09-21 Here are the refereed proceedings of the 8th International Conference on Artificial Intelligence and Symbolic Computation AISC 2006 The book presents 18 revised full papers together with 4 invited papers organized in topical sections on artificial intelligence and theorem proving symbolic computation constraint satisfaction solving and mathematical knowledge management Coverage includes mathematical foundations implementations and applications in industry and academia

Real Algebraic Geometry and Ordered Structures Charles N. Delzell,James J. Madden,2000 This volume contains 16 carefully refereed articles by participants in the Special Semester and the AMS Special Session on Real Algebraic Geometry and Ordered Structures held at Louisiana State University and Southern University Baton Rouge The 23 contributors to this volume were among the 75 mathematicians from 15 countries who participated in the special semester Topics include the topology of real algebraic curves Hilbert s 16th problem moduli of real algebraic curves effective sums of squares of real forms Hilbert s 17th problem efficient real quantifier elimination subanalytic sets and stratifications semialgebraic singularity theory radial vector fields exponential functions and valuations on nonarchimedean ordered fields valued field extensions partially ordered and lattice ordered rings rings of continuous functions spectra of rings and abstract spaces of higher level orderings and real places This volume provides a good overview of the state of the art in this area in the 1990s It includes both expository and original research papers by top workers in this thriving field The authors and editors strived to make the volume useful to a wide audience including students and researchers interested in real algebraic geometry and ordered structures two subjects that are obviously related but seldom brought together

Computer Aided Verification Constantin Enea,Akash Lal,2023-07-17 The open access proceedings set LNCS 13964 13965 13966 constitutes the refereed proceedings of the 35th International Conference on Computer Aided Verification CAV 2023 which was held in Paris France in July 2023 The 67 full papers presented in these proceedings were carefully reviewed and selected from 261 submissions The have been organized in topical sections as follows Part I Automata and logic concurrency cyber physical and hybrid systems synthesis Part II Decision procedures model checking neural networks and machine learning Part II Probabilistic systems security and quantum systems software verification

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