

Quantifier Elimination by Cylindrical Algebraic Decomposition Based on Regular Chains

Changbo Chen
Chongqing Key Laboratory of Automated
Reasoning and Cognition, Chongqing Institute of
Green and Intelligent Technology, CAS
changbo.chen@hotmail.com

Marc Moreno Maza
ORCCA, University of Western Ontario
moreno@csd.uwo.ca

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, SYNRRAC⁴, *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/>

⁴SYNRRAC: <http://jp.fujitsu.com/group/labs/techinfo/freesware/synrrac/>

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

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