

raSAT : SMT Solver for Polynomial Constraints

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Abstract. This paper presents an SMT solver **raSAT** for polynomial constraints, which aims to handle them over both reals and integers with simple unified methodologies: (1) **raSAT loop** for inequations, which extends the *interval constraint propagation* with testing to accelerate SAT detection, and (2) a non-constructive reasoning for equations over reals, based on the Intermediate Value Theorem.

1 Introduction

Polynomial constraint solving is to find an instance that satisfies given polynomial inequations/equations. Various techniques are implemented in SMT solvers, e.g., for reals (*QF-NRA*), **Cylindrical algebraic decomposition** (RAHD[15], Z3 from 4.3[10]), **Virtual substitution** (SMT-RAT[5], Z3 from 3.1), **Interval constraint propagation (ICP)**[1] (iSAT3[6], dReal[8], RSolver[16]), and **CORDIC encoding** (CORD[7]). For integers (*QF-NIA*), we have **Bit-blasting** (UCLID[3], MiniSmt [17]) and **Linearization** (Barcelogic[2]).

This paper presents an SMT solver **raSAT**³ (refinement of approximations for SAT) for polynomial constraints over both reals and integers. For inequations, it applies a simple iterative approximation refinement, **raSAT loop**, which extends ICP with testing to boost SAT detection. For equations, a non-constructive reasoning based on the Intermediate Value Theorem is employed (Section 4).

In a floating point arithmetic, round-off errors may violate the soundness. To get rid of such traps, we apply the outward rounding [9] in an interval arithmetic. We also integrate **iRRAM**⁴, which guarantees the round-off error bounds, to confirm that a detected SAT instance is really SAT.

Currently, **raSAT** applies an incremental search, *incremental widening* and *deepening*, and an SAT-directed strategy based on measures, *SAT likelihood* and *sensitivity* (Section 3), but does not have UNSAT-directed strategies, e.g., UNSAT core. Note that the sensitivity works only with Affine intervals [14].

At the SMT Competition 2015, **raSAT** participated two categories of main tracks, *QF-NRA* and *QF-NIA*. **raSAT** is originally developed for *QF-NRA*, however *QF-NIA* is fairly easy to adapt, i.e., stop interval decompositions when the width becomes smaller than 1, and generate integer-valued test instances.

³ Available at <http://www.jaist.ac.jp/~s1310007/raSAT/index.html>

⁴ Available at <http://irram.uni-trier.de>

As the overall rating (Main Track), **raSAT** is 8th among 19 SMT solvers⁵. The results are summarized as

- 3rd in *QF_NRA*, **raSAT** solved 7952 over 10184 (where Z3 4.4 solves 10000).
- 2nd in *QF_NIA*, **raSAT** solved 7917 over 8475 (where Z3 4.4 solves 8459; CVC4 (exp) solves 8277, but with one wrong detection).

2 ICP Overview and raSAT Loop

Our target problem is solving nonlinear constraints. First, we discuss on solving polynomial inequations, and that for equations are shown later in Section 4. Let \mathbb{R} be the set of real numbers and $\mathbb{R}^\infty = \mathbb{R} \cup \{-\infty, \infty\}$. The normal arithmetic on \mathbb{R} is extended to those on \mathbb{R}^∞ as in [13]. The set of all intervals is defined as $\mathbb{I} = \{[l, h] \mid l \leq h \in \mathbb{R}^\infty\}$. A box for a sequence of variables x_1, \dots, x_n is of the form $B = I_1 \times \dots \times I_n$ where $I_1, \dots, I_n \in \mathbb{I}$.

Definition 1. A polynomial inequality constraint is

$$\psi(x_1, \dots, x_n) = \bigwedge_{j=1}^m p_j(x_1, \dots, x_n) > 0$$

where $p_j(x_1, \dots, x_n) > 0$ is an atomic polynomial inequation (API). When x_1, \dots, x_n are clear from the context, we denote ψ for $\psi(x_1, \dots, x_n)$, p_j for $p_j(x_1, \dots, x_n)$, and $\text{var}(p_j)$ for the set of variables appearing in p_j .

As an SMT problem, ψ is satisfiable (SAT) if there exists an assignment on variables that makes it *true*. Otherwise, ψ is said to be unsatisfiable (UNSAT). Let $\mathbb{S}(\psi) = \{(r_1, \dots, r_n) \in \mathbb{R}^n \mid \psi(r_1, \dots, r_n) = \text{true}\}$.

Algorithm 1 ICP starting from the initial box $B_0 = I_1 \times \dots \times I_n$

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1:  $S \leftarrow \{B_0\}$  ▷ Set of boxes
2: while  $S \neq \emptyset$  do
3:    $B \leftarrow S.\text{choose}()$  ▷ Get one box from the set
4:    $B' \leftarrow \text{prune}(B, \psi)$ 
5:   if  $B' = \emptyset$  then ▷ The box does not satisfy the constraint
6:      $S \leftarrow S \setminus \{B\}$ 
7:     continue
8:   else if  $B'$  satisfies  $\psi$  by using IA then
9:     return SAT
10:  else ▷ IA cannot conclude the constraint  $\implies$  Refinement Step
11:     $\{B_1, B_2\} \leftarrow \text{split}(B')$  ▷ split  $B'$  into two smaller boxes  $B_1$  and  $B_2$ 
12:     $S \leftarrow (S \setminus \{B\}) \cup \{B_1, B_2\}$ 
13:  end if
14: end while
15: return UNSAT

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⁵ <http://smtcomp.sourceforge.net/2015/results-competition-main.shtml>

2.1 ICP Overview

Starting with a box B , ICP [1] tries to prove UNSAT/SAT of ψ inside B by an interval arithmetic (IA). If it fails, it iteratively decomposes boxes, and IA and constraint propagation are applied. Algorithm 1 describes the basic ICP for solving polynomial inequations where two functions $prune(B, \psi)$ and $split(B)$ satisfy the following properties.

- If $B' = prune(B, \psi)$, then $B' \subseteq B$ and $B' \cap \mathbb{S}(\psi) = B \cap \mathbb{S}(\psi)$.
- If $\{B_1, B_2\} = split(B)$, then $B = B_1 \cup B_2$ and $B_1 \cap B_2 = \emptyset$.

ICP concludes SAT (line 8) only when it finds a box in which the constraint becomes valid (IA-valid) by an IA. Although the number of boxes to be checked may be exponentially many, ICP always detects SAT of the inequations ψ if I_1, \dots, I_n are bounded (Fig. 1a). ICP can detect UNSAT (Fig. 1b); however ICP may miss to detect UNSAT in *kissing* or *convergent* cases (Fig. 1c,d).

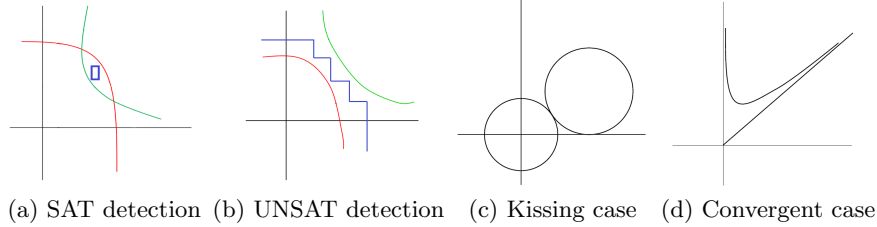


Fig. 1: Scenarios of solving polynomial inequations with ICP

2.2 raSAT Loop

ICP is extended to **raSAT** loop [11], which is displayed in Algorithm 2.

Its implementation **raSAT** adapts various IAs including Affine Intervals (AI) [4, 14, 11] and Classical Interval (CI) [13]. An AI introduces noise symbols ϵ 's, which are interpreted to values in $[-1, 1]$. AIs vary depending on the treatments of the multiplication among noise symbols. For the multiplication of the same noise symbols, AF_2 [12] describes by ϵ_+ (or ϵ_-), which is interpreted in $[0, 1]$ (or $[-1, 0]$), and CAI [11] describes $\epsilon\epsilon = |\epsilon| + [-\frac{1}{4}, 0]$. Mostly, the product of different noise symbols are simply regarded as any value in $[-1, 1]$ (e.g., ϵ_\pm).

Although precision is incomparable, an AI partially preserves the dependency among values, which is lost in CI. For instance, consider $x \in [2, 4] = 3 + \epsilon$. Then, $x - x$ is evaluated to $[-2, 2]$ by CI, where 0 by an AI.

Example 1. Let $g = x^3 - 2xy$, $x = [0, 2] = 1 + \epsilon_1$, and $y = [1, 3] = 2 + \epsilon_2$. *CI* estimates the range of g as $[-12, 8]$, *AF₂* does $-3 - \epsilon_1 - 2\epsilon_2 + 3\epsilon_+ + 3\epsilon_\pm (= [-9, 6])$, and *CAI* does $[-4, -\frac{11}{4}] + [-\frac{1}{4}, 0]\epsilon_1 - 2\epsilon_2 + 3|\epsilon_1| + [-2, 2]\epsilon_\pm (= [-8, 4.5])$.

Algorithm 2 **raSAT** loop starting from the initial box $\Pi = \bigwedge_{i=1}^n x_i \in I_i^0$

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1: while  $\Pi$  is satisfiable do ▷ Some more boxes exist
2:    $\pi = \{x_i \in I_{ik} \mid i \in \{1, \dots, n\}, k \in \{1, \dots, i_k\}\} \leftarrow$  a solution of  $\Pi$ 
3:    $B \leftarrow$  the box represented by  $\bigwedge_{i=1}^n \bigwedge_{k=1}^{i_k} x_i \in I_{ik}$ 
4:   if  $B$  does not satisfy  $\psi$  by using IA then
5:      $\Pi \leftarrow \Pi \wedge \neg(\bigwedge_{i=1}^n \bigwedge_{k=1}^{i_k} x_i \in I_{ik})$ 
6:   else if  $B$  satisfies  $\psi$  by using IA then
7:     return SAT
8:   else if  $B$  satisfies  $\psi$  by using testing then ▷ Different from ICP
9:     return SAT
10:  else ▷ Neither IA nor testing conclude the constraint  $\implies$  Refinement Step
11:    choose  $(x_i \in I_{ik}) \in \pi$  such that  $\forall k_1 \in \{1, \dots, i_k\} I_{ik} \subseteq I_{ik_1}$ 
12:     $\{I_1, I_2\} \leftarrow \text{split}(I_{ik})$  ▷ split  $I_{ik}$  into two smaller intervals  $I_1$  and  $I_2$ 
13:     $\Pi \leftarrow \Pi \wedge (x_i \in I_{ik} \leftrightarrow (x_i \in I_1 \vee x_i \in I_2)) \wedge \neg(x_i \in I_1 \wedge x_i \in I_2)$ 
14:  end if
15: end while
16: return UNSAT

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3 SAT directed Strategies of raSAT

Performance of ICP is affected by the number of variables, since the initial box $I_1 \times \dots \times I_n$ may be decomposed into exponentially many boxes. Thus, strategies for controlling a search among boxes and selecting a box / a variable to decompose are crucial for practical efficiency.

3.1 Incremental Search

Two incremental search strategies are prepared in **raSAT**.

Incremental Widening. Given $0 < \delta_0 < \delta_1 < \dots < \delta_k = \infty$, *incremental widening* starts with $B_0 = [-\delta_0, \delta_0] \times \dots \times [-\delta_0, \delta_0]$, and if ψ remains UNSAT, then enlarge the box to $B_1 = [-\delta_1, \delta_1] \times \dots \times [-\delta_1, \delta_1]$. This continues until either timeout or the result obtained. In **raSAT**, *AF*₂ is used for B_i if $i \neq k$, and *CI* is used for $\delta_k = \infty$.

Incremental Deepening. To combine depth first and breadth first searches among decomposed boxes, **raSAT** applied *incremental deepening*. Let $\gamma_0 > \gamma_1 > \dots > 0$. It applies a threshold γ , such that no more decomposition occurs when the size of a box becomes smaller than γ . γ is initially set to γ_0 . If neither SAT nor UNSAT is detected, **raSAT** restarts with the threshold γ_1 (Fig. 2). This continues until either timeout or the result obtained.

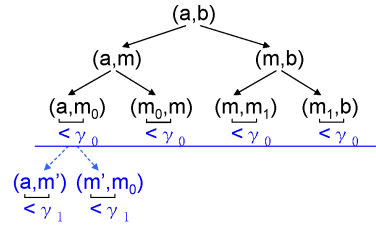


Fig. 2: Incremental Deepening

3.2 SAT Directed Heuristics Measure

To reduce an explosion of the number of decomposed boxes, **raSAT** prepares a strategy to select a variable at a box decomposition. (1) First, select a least likely satisfiable *API* with respect to *SAT-likelihood*. (2) Then, choose a most likely influential variable in such *API* with respect to the *sensitivity*. We assume an Affine interval (AI) for an interval arithmetic (IA).

In line 3 of Algorithm 2, let an AI estimate the range $range(g_j, B)$ of each polynomial g_j in a box B as $[c_1, d_1]\epsilon_1 + \dots + [c_n, d_n]\epsilon_n$. Then, $range(g_j, B)$ is evaluated by instantiating $[-1, 1]$ to ϵ_i . We define

- The *SAT-likelihood* of an *API* $g_j > 0$ is $|I \cap (0, \infty)|/|I|$ for $I = range(g_j, B)$.
- The *sensitivity* of a variable x_i in an *API* $g_j > 0$ is $max(|c_i|, |d_i|)$.

Example 2. In Example 1, *SAT-likelihood* of g is $0.4 = \frac{6}{9-(-6)}$ by AF_2 and $0.36 = \frac{4.5}{4.5-(-8)}$ by CAI . The sensitivity of x is 1 by AF_2 and $3\frac{1}{4}$ by CAI , and that of y is 2 by both.

Our strategy consists of three steps:

1. Choice of an *API* with the least *SAT likelihood*.
2. Choice of a variable with the largest *sensitivity* in the *API*.
3. Choice of a box with the largest *SAT likelihood*, where the *SAT-likelihood* of a box B is the least *SAT-likelihood* among *APIs* on B .

The first two steps selects a variable to apply the interval decomposition and the testdata generation. After a box decomposition is applied, the last step compares *SAT-likelihood* of all boxes (including newly decomposed boxes) to select one to explore next. At the testdata generation, **raSAT** observes the sign of the coefficient of the noise symbol with the largest sensitivity. If positive, first take the upper bound; otherwise, the lower bound. The rest is generated randomly.

The strategy is evaluated on Zankl and Meti-Tarski families of *QF-NRA*. As a comparison with other ICP-based solvers, we compare **raSAT** with a random choice (*Random*), **raSAT** with the strategy above (**raSAT**), **iSAT3**, and **dReal**.

Note that (1) **iSAT3** solves over $[-1000, 1000]$ due to the system restriction, while all others solve over $[-\infty, \infty]$, and (2) SAT of **dReal** is δ -SAT (SAT under tolerance of the width δ); thus **dReal** sometimes answers SAT even for UNSAT problems. The timeout is set to 500 seconds (on Intel Xeon E5-2680v2 2.80GHz and 4GB of RAM), and the time shows the total of successful cases. Matrix-1, Matrix-2~5, and Meti-Tarski have 53, 96, and 4884 inequality problems resp.

Benchmark	<i>Random</i>		raSAT		iSAT3		dReal	
Matrix-1 (SAT)	19	230.39(s)	25	414.99	11	4.68	46*	3573.43
Matrix-1 (UNSAT)	2	0.01(s)	2	0.01	3	0.00	0	0.00
Matrix-2~5 (SAT)	1	13.43(s)	11	1264.77	3	196.40	19*	2708.89
Matrix-2~5 (UNSAT)	8	0.37(s)	8	0.38	12	8.06	0	0.00
Meti-Tarski (SAT)	3451	895.14(s)	3473	419.25	2916	811.53	3523*	441.35
Meti-Tarski (UNSAT)	1060	233.46(s)	1052	821.85	1225	73.83	1197	55.39

(* means δ -SAT)

We observe that the strategy is effective for SAT-detection in large problems, like Matrix-2~5 (in Zankl benchmarks), which often have more than 50 variables (Meta-Tarski has mostly less than 10 variables, and Matrix-1 has mostly less than 30 variables). Comparing with the state-of-the-art tool **Z3 4.4** on Matrix-2~5, the differences appear that **Z3 4.4** solely solves Matrix-3-7, 4-12, and 5-6 (which have 75, 200, and 258 variables), and **raSAT** solely solves Matrix-2-3, 2-8, 3-5, 4-3, and 4-9 (which have 57, 17, 81, 139, and 193 variables).

4 Extension for Equations Handling

Single Equation. A single equation ($g = 0$) can be solved by finding 2 test cases with $g > 0$ and $g < 0$. Then, $g = 0$ holds somewhere in between by the Intermediate Value Theorem.

Lemma 1. For $\psi = \bigwedge_{j=1}^m g_j > 0 \wedge g = 0$. Suppose a box B and let $[l_g, h_g] = \text{range}(g, B)$,

- (i) If either $l_g > 0$ or $h_g < 0$, then $g = 0$ (thus ψ) is UNSAT in B .
- (ii) If $\bigwedge_{j=1}^m g_j > 0$ is IA-valid in B and there are $\mathbf{t}, \mathbf{t}' \in B$ with $g(\mathbf{t}) > 0$ and $g(\mathbf{t}') < 0$, then ψ is SAT.

If neither (i) nor (ii) holds, **raSAT** continues the decomposition.

Example 3. Let $\psi = f(x, y) > 0 \wedge g(x, y) = 0$. Suppose we find a box $B = [a, b] \times [c, d]$ such that $f(x, y) > 0$ is IA-valid in B . (Fig. 3a). In addition, if we find two points (u_1, v_1) and (u_2, v_2) in B such that $g(u_1, v_1) > 0$ and $g(u_2, v_2) < 0$, then the constraint is satisfiable by Lemma 1.

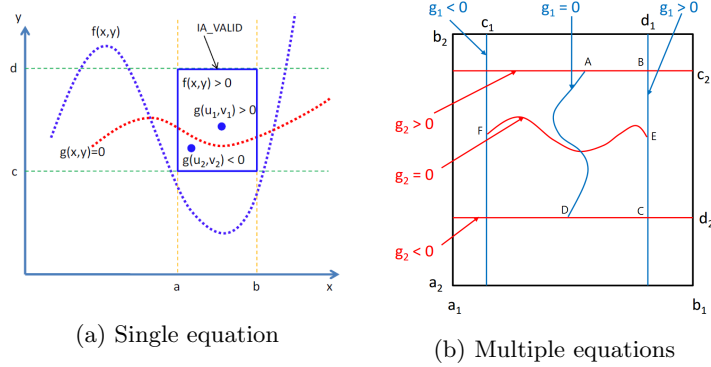


Fig. 3: Example on solving equations using the Intermediate Value Theorem

Multiple Equations. Multiple equations are solved by repeated applications of the Intermediate Value Theorem. Let $\bigwedge_{j=1}^m g_j = 0$ and $B = [l_1, h_1] \times \cdots [l_n, h_n]$ with $m \leq n$. Let $V = \{x_1, \dots, x_n\}$ be the set of variables. For $V' = \{x_{i_1}, \dots, x_{i_k}\} \subseteq V$, we denote $B \downarrow_{V'}$ and $B \uparrow_{V'}$ for $\{(r_1, \dots, r_n) \in B \mid r_i = l_i \text{ for } i = i_1, \dots, i_k\}$ and $\{(r_1, \dots, r_n) \in B \mid r_i = h_i \text{ for } i = i_1, \dots, i_k\}$, respectively.

Definition 2. A sequence (V_1, \dots, V_m) of subsets of V is a check basis of (g_1, \dots, g_m) in a box B , if, for each j, j' with $1 \leq j, j' \leq m$,

1. $V_j (\neq \emptyset) \subseteq \text{var}(g_j)$,
2. $V_j \cap V_{j'} = \emptyset$ if $j \neq j'$, and
3. either $g_j > 0$ on $B \uparrow_{V_j}$ and $g_j < 0$ on $B \downarrow_{V_j}$, or $g_j < 0$ on $B \uparrow_{V_j}$ and $g_j > 0$ on $B \downarrow_{V_j}$.

Lemma 2. For a polynomial constraint containing multiple equations

$$\psi = \bigwedge_{j=1}^m g_j > 0 \wedge \bigwedge_{j=m+1}^{m'} g_j = 0$$

and $B = [l_1, h_1] \times \cdots [l_n, h_n]$, assume that

1. $\bigwedge_{j=1}^m g_j > 0$ is IA-valid in B , and
2. there is a check basis $(V_{m+1}, \dots, V_{m'})$ of $(g_{m+1}, \dots, g_{m'})$ in B .

Then, ψ has a SAT instance in B .

The idea is, from the Intermediate Value Theorem, each $j \in \{m+1, \dots, m'\}$, g_j has a $n - |V_j|$ dimensional surface of null points of g_j between $B \uparrow_{V_j}$ and $B \downarrow_{V_j}$. Since V_j 's are mutually disjoint (and g_j 's are continuous), we have the intersection of all such surfaces of null points with the dimension $n - \sum_{j=m+1}^{m'} |V_j|$. Thus, this method has a limitation that the number of variables must be greater than or equal to the number of equations.

Fig. 3b illustrates Lemma 2 for $m = 0$ and $m' = n = 2$. The blue and red lines represent the null points of $g_1(x, y)$ and $g_2(x, y)$ in $[c_1, d_1] \times [c_2, d_2]$, respectively. They must have an intersection somewhere.

The table below shows preliminary experiments on benchmarks with equality constraints. Note that Keymaera benchmark consists of 612 problems, but we do not know yet the exact numbers of SAT and UNSAT problems

Benchmark	raSAT		Z3 4.4		iSAT3	
Zankl (SAT) (11)	11	0.07(s)	11	0.17	0	0.00
Zankl (UNSAT) (4)	4	0.17(s)	4	0.02	4	0.05
Meti-Tarski (SAT) (3528)	875	174.90(s)	1497	20.21	1	0.28
Meti-Tarski (UNSAT) (1573)	781	401.15(s)	1116	61.13	1075	22.6
Keymaera (SAT)	0	0.00(s)	0	0.00	0	0.00
Keymaera (UNSAT)	312	66.63(s)	610	2.92	226	1.63

5 Conclusion

This paper presented an SMT solver **raSAT** for polynomial constraints (available at <http://www.jaist.ac.jp/~s1310007/raSAT/index.html>), which aims to handle them over both reals and integers with simple unified methodologies. There are lots of future works and improvements, e.g.,

- Support mixed integers (QF_NIRA).
- Implement UNSAT-directed strategies, e.g. UNSAT core.
- Set search bounds based on the cylindrical algebraic decomposition.
- Apply Groebner basis to overcome current limitation that the number of variables must be greater than or equal to the number of equations.

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