IPO-MAXSAT: Combining the In-Parameter-Order Strategy for Covering Array Generation with MaxSAT solving

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Generation of Covering Arrays for Abstract Combinatorial Test Suites

Covering Arrays for Combinatorial Testing
- Covering Arrays (CAs) provide the theoretical means for Combinatorial Testing (CT).
- Columns of a CA map to the parameters of a system under test (SUT).
- Rows of a CA encode the individual test cases.
- Their combinatorial properties guarantee that derived test sets cover all t-way interactions.
- To apply CT to arbitrary SUTs, we need to be able to generate arbitrary CAs.

The Covering Array Generation Problem
- Given a strength t, a number of columns k and an alphabet size v.
- Construct a covering array CA((v); t, k, v) minimizing the number of rows N.
- Exact and direct constructions of CAs exist only for some corner cases.
- For general applications we need heuristic algorithms for arbitrary CA generation.

Input Model
Test Set Generator
t-way Test Set
Test Execution
Execution Oracle
Locating Faults

The IPO Strategy for CA Generation
- A popular method for CA generation, realized in many algorithms.
- An array is extended horizontally and, if necessary, vertically until the desired CA is generated.
- Initialization: A $v \times t$ array is initialized with all $v \times t$-tuples.
  - First four rows of columns a and b in Figure 1.
- Horizontal extension: The CA is extended with an additional column.
  - A greedy construction attempts to cover many t-way interactions.
  - Blue (new column) in Figure 1.
- Vertical extension: If any t-way interactions are not covered, then star-values can be assigned and the array is extended with new rows until all t-way interactions are covered.
  - Red (star-values) and green (new rows) in Figure 1.
- Star-values: Array cells that are not yet assigned a value. New rows in vertical extension are initialized with star-values.

Results & Lessons learned
- We compare against:
  - SIPO: IPO strategy with Simulated Annealing [1];
  - FIPOG: a state-of-the-art IPO algorithm for CA generation [2];
  - NIST Tables: largest online repository of CAs [3], generated with IPOG-F [4];
  - CA Tables: the best known upper bound on the number of rows N for which a CA CA((v); t, k, v) exists [5].
- We present experimental results for CA((v); 3, k, 2):

<table>
<thead>
<tr>
<th>Number of columns k</th>
<th>Number of rows N</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
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<tr>
<td>10</td>
<td>10</td>
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<td>40</td>
<td>40</td>
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<tr>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>

Figure 1: Schematics of the IPO strategy for a binary CA ($v = 2$) of strength $t = 2$.

Figure 2: Size (number of rows $N$) of generated CA((v); 3, k, 2) for $k \leq 47$.

Figure 3: Runtimes in seconds for generating a CA((v); 3, k, 2) for $k \leq 47$.

IPO-MAXSAT
- Idea: Use MaxSAT solvers to find optimal horizontal extensions
- translate MaxSAT instance:
  $\{\neg x_1 \vee \neg x_2, \ldots, (20 \cdot x_1 \vee x_3 \vee x_6)\}$
- solve MaxSAT model:
  $\{0,1,0,1,1,...\}$
- Star-value optimization is included in horizontal extension.
- Soft clauses encode our optimization goals:
  - Primary objective: Cover a maximal number of t-way interactions.
  - Secondary objective: Keep as many star-values as possible.


[2] Kristoffer Kleine and Dimitris E. Simos. An efficient design and implementation of the in-parameter-order algorithm. For Abstract Combinatorial Test Suites
- Generation of Covering Arrays for Combinatorial Testing


- Primary objective: Cover a maximal number of t-way interactions.
- Secondary objective: Keep as many star-values as possible.


SBA Research (08.14.8) is a COMET Centre within the framework of COMET – Competence Centers for Excellent Technologies Programme and funded by BMW, BMVIT, and the federal state of Vienna. The COMET Programme is managed by FFG.