Multi-Criteria Function Inlining for Hard Real-Time Systems

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Motivation

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- **Hard real-time systems:**
  - worst-case execution time (WCET),
  - code size,
  - energy consumption.

Outline

Function inlining

Function inlining

```
int max (int i, int j)
{
 return i>j?i:j;
}

int main()
{
 ...
 a = max(c,d);
 ...
 b = max(f,g);
}
```

```
int main()
{
 ...
 a = c>d?c:d;
 ...
 b = f>g?f:g;
}
```

Function inlining

$$X = \left\{ \begin{array}{c} x = (x_1, x_2, \ldots, x_N), \\ x_i \in \{0, 1\} \quad \forall i = 1, 2, \ldots, N. \end{array} \right\} \tag{1}$$

$$U = (\text{WCET},\ \text{Code Size},\ \text{Energy Consumption}) \tag{2}$$

$$\min_{x \in X} U(x). \tag{3}$$

Multi-objective problem

Multi-objective optimization

x **dominates** y ($x \prec y$), if

$$\begin{aligned} \forall t \in \{1, 2, \dots, s\} \quad & f_t(x) \leq f_t(y), \\ \exists r \in \{1, 2, \dots, s\} : \quad & f_r(x) < f_r(y). \end{aligned} \tag{4}$$

A solution that is not dominated by any other solution is called **Pareto optimal**.

Pareto optimal front PF^*:

$$PF^* = \{F(x) | x \text{ is Pareto optimal}\}. \tag{5}$$

Evolutionary algorithm

Algorithm 1 Evolutionary algorithm.

```
Input: initialized initial population, stopping criterion;
Output: approximated Pareto front.
while Stopping criterion is not reached do
    Crossover
    Mutation
    Selection
end while
```

Evaluation

Setup

- WCET-aware C compiler framework WCC [2]
- ARM7TDMI micro-controller in the thumb mode
- Compiler's optimization level O2
- PolyBench, MediaBench, MRTC, DSPstone, and UTDSP with annotated loop bounds from the TACLeBench project [3]
- static WCET analyzer aiT 18.10 [1]
- modified GDE3 [4] and MBPOA [5]

Control parameters

- Crossover $CR \in \{0.1, 0.2, 0.3, \ldots, 0.8\}$;
- Bandwidth $b \in \{0, 5, 20, 50, 100, 500, 1000\}$;
- Scaling Factor $F \in \{0.2, 0.5, 1.0, 2.0, 5.0, 10.0\}$.

Quality indicators

Non-dominance ratio:

$$NR_A = \frac{Unique(A \cap D)}{|D|}. \tag{6}$$

Coverage:

$$C_A = 1 - \frac{|A \cap D|}{|A|}. \tag{7}$$

Internal non-dominance ratio:

$$INR_A = \frac{Unique(A \cap D)}{|A|}. \tag{8}$$

Quality indicators

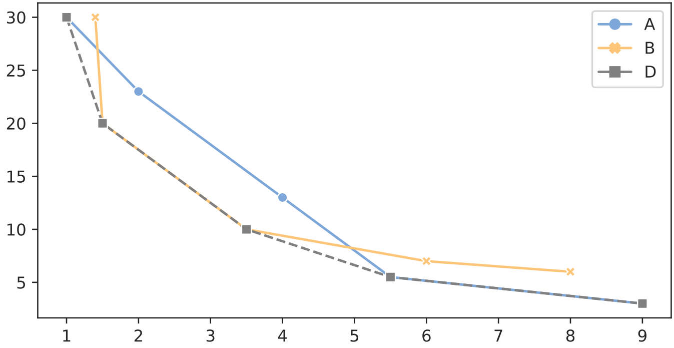

Figure 1: Example of two sets A and B with the set D of all non-dominated points of the union of sets $(A \cup B)$.

Crossover

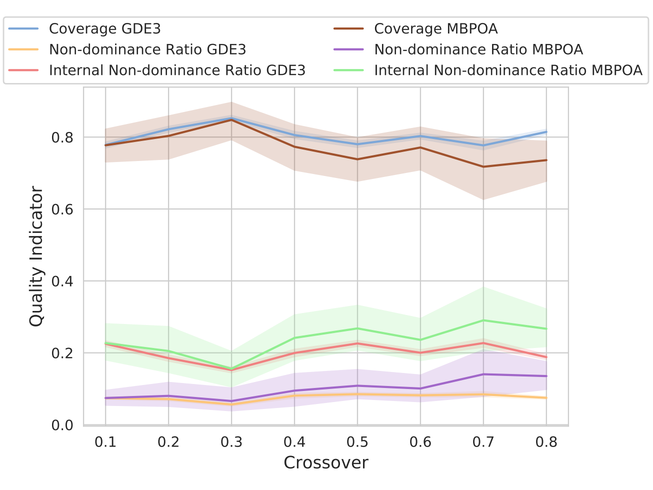

Figure 2: Quality indicators as functions of crossover.

Bandwidth

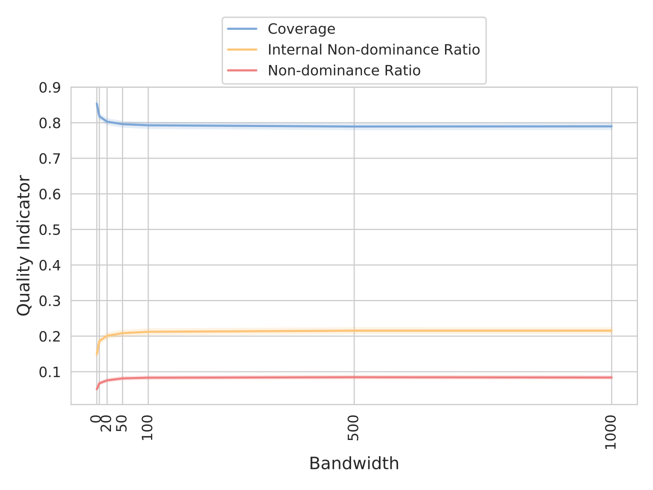

Figure 3: Quality indicators as functions of GDE3's bandwidth.

Scaling factor

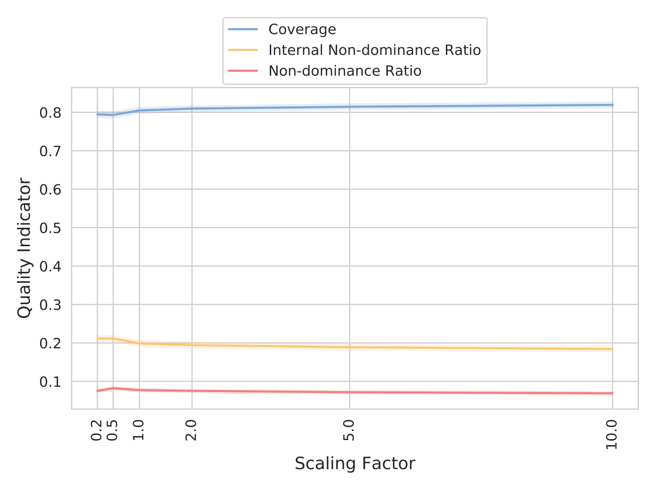

Figure 4: Quality indicators as functions of GDE3's scaling factor.

Comparison of algorithms

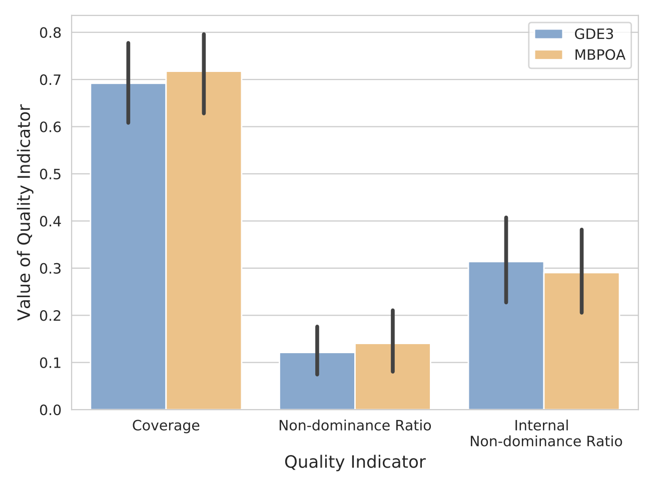

Figure 5: Comparison of quality indicators for GDE3 and MBPOA with fixed control parameters.

Benchmarks

Benchmark	Dimension of the search space
cjpeg_jpeg6b_wrbmp	16
codecs_codrle1	25
codecs_dcodhuff	18
gsm_decode	23
huffc	86
md5	13
qurt	125
st	129
trisolv	126

Benchmarks

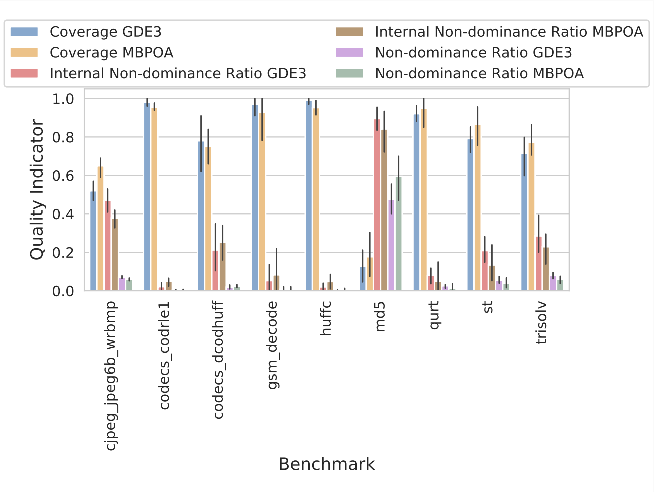

Figure 6: Quality indicators for the fixed parameters.

Worst-case execution time

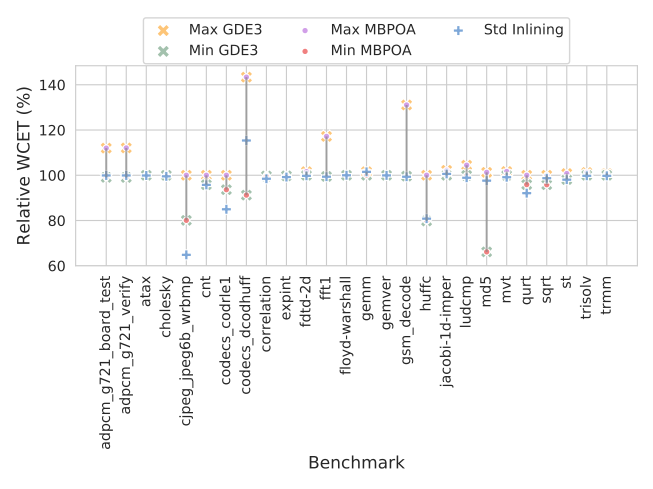

Figure 7: Worst-case execution time (WCET).

Code size

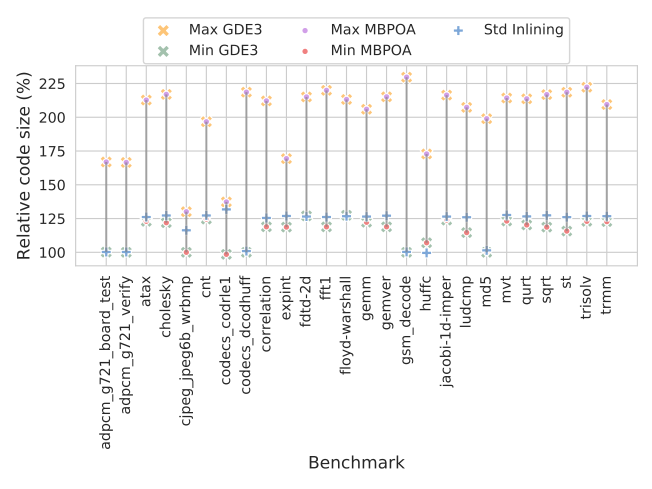

Figure 8: Code size.

Energy consumption

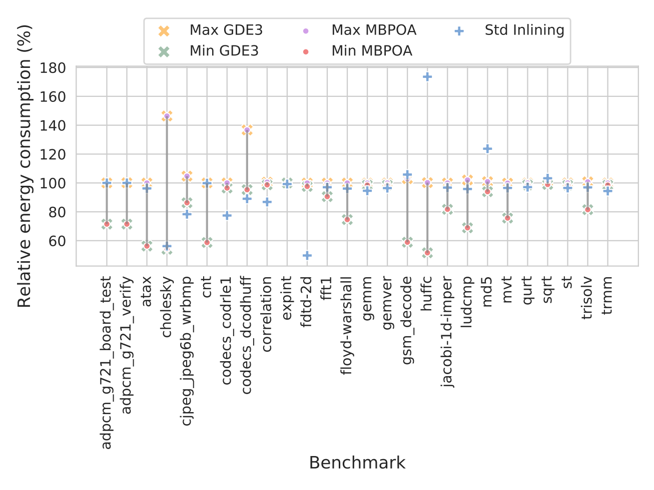

Figure 9: Energy consumption.

Conclusion

Conclusion

- Multi-objective function inlining considering WCET, code size, and energy consumption as objectives;
- The compiler returns a set of the best solutions;
- We analyzed two evolutionary algorithms;
- The result of the standard function inlining was compared to the multi-objective solution set.

Future Work

- Minimize the number of expensive evaluations by using surrogate models
- Other compiler-based optimizations

References

[1] AbsInt Angewandte Informatik, GmbH. *aiT Worst-Case Execution Time Analyzers*. 2018.

[2] H. Falk and P. Lokuciejewski. "A Compiler Framework for the Reduction of Worst-Case Execution Times". In: *Real-Time Systems* 46.2 (2010), pp. 251–300.

[3] H. Falk et al. "TACLeBench: A Benchmark Collection to Support Worst-Case Execution Time Research". In: *Proc. of the 16th International Workshop on Worst-Case Execution Time Analysis*. Vol. 55. OASIcs. 2016, 2:1–2:10.

[4] S. Kukkonen and J. Lampinen. "GDE3: the third evolution step of generalized differential evolution". In: *Proc. of the IEEE Congress on Evolutionary Computation* 1 (2005), pp. 443–450.

[5] L. Wang et al. "MBPOA-based LQR controller and its application to the double-parallel inverted pendulum system". In: *Engineering Applications of Artificial Intelligence* 36 (2014), pp. 262–268.