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Non-Transparent Debugging
For Software-Pipelined Loops

Hugo Venturini∗
hugo.venturini@imag.fr
Verimag / STMicroelectronics

Frédéric Riss
frederic.riss@st.com
STMicroelectronics

Jean-Claude Fernandez
jean-claude.fernandez@imag.fr
Verimag

Miguel Santana
miguel.santana@st.com
STMicroelectronics

ABSTRACT
This paper tackles the problem of providing correct information about program variable values in a software-pipelined loop through a non-transparent debugging approach. Since modern processors provide instruction level parallelism, software pipelining techniques have been developed to achieve better performances, especially in the context of embedded systems. Indeed, the effectiveness of software pipelining on such systems has been demonstrated both theoretically and experimentally. As it overlaps iterations and reorders statements, it also makes standard debugging information irrelevant. Hence debugging a loop which has been software-pipelined becomes very difficult. In this paper, we propose a solution relying on selected information to be generated by the compiler and an algorithm for the debugger not to mislead the user.

ACM Classification
D.2.5 [Software Engineering]: Testing and Debugging

General Terms
Algorithms, Experimentation

1. KEYWORDS
compiler, debugger, non-transparent debugging, software-pipelining

2. INTRODUCTION
Over the last thirty years, program optimizers’ technologies improved significantly faster than debuggers’ technologies. This disparity is reflected in the literature; many books and articles treat optimizations but very few address the debugging of optimized code.

∗supported by a CIFRE STMicroelectronics industrial grant

Nevertheless, in the context of embedded systems, debugging the optimized code is a necessity. The programmer may need to debug his program in real-life conditions, i.e. onto the embedded systems which may not accept the unoptimized program due to constraints. Optimizations are often required because of the real time and memory constraints imposed, especially on embedded systems. Moreover, the overhaul will be done on an optimized program so the programmer has to test and debug the latter on the device it is targeted to.

A wide range of processors, e.g. superscalars or VLIW (Very Long Instruction Word) use parallelism mechanisms which can be hardware and software. One of these optimizing methods is called software-pipelining. It is performed by the compiler and allows the use of parallelism inherent in an application.

Software pipelining is a type of instruction scheduling where the goal is to construct an equivalent loop of minimum length by overlapping computations from different iterations of the original loop. Hence, it makes standard debug information obsolete. Debugging a loop which has been software-pipelined would not make sense without a correct mapping between the source code and the assembly code. Instructions generated from various source statements are duplicated, combined, moved, deleted and interleaved with instructions from other source statements. It becomes very difficult to decide where in the target program any given source statement begins or ends. Thus, breakpoints set in the source code may not find their equivalent in the optimized program and vice versa. Debugging the optimized code becomes very complicated.

We propose an approach in which the compiler generates more information than it does under the current standard. We have designed an algorithm for the debugger to accurately use this information and answer the following question: When retrieving the value of a variable at a given address, which iteration count produced the value? The idea is not to hide anything from the user, but rather to guide the user through the debugging process. When a variable’s assignment has been delayed, not only do we provide the variable’s current value, but we also provide the delay of assignment. Hence the user knows exactly the behavior of the software-pipelined program. The experimentation context is a retargetable compiler for embedded processors which aims at providing state-of-the-art optimizations: MMDSP+ C Compiler. It is built around the CoSy compiler development suite [2] with an in-house back-end [5].

The paper is organized as follows: Section 3 describes software-pipelining loops and provides useful definitions and an example to
illustrate it. Section 4 reviews existing problems due to optimizing programs. Section 5 presents the contributions of our work. Section 6 details debug information to be collected by the compiler. Section 7 describes the algorithm to be implemented by the debugger to solve the issue. We give the tool framework and experimentation in section 8. Section 9 reviews related works since 1982. Finally section 10 concludes and discusses future works.

3. SOFTWARE PIPELINING

3.1 Overview

Software pipelining is a type of instruction scheduling where the goal is to construct an equivalent loop of minimum length by overlapping computations from different iterations of the original loop. It can be used on many architectures, especially those which allow instruction-level parallelism (ILP), but it is particularly efficient on VLIW processors. One VLIW instruction encodes multiple operations; specifically, one instruction encodes at least one operation for each execution unit of the device. For example, if a VLIW device has five execution units, then a VLIW instruction for that device would have five operation fields, each field specifying what operation should be done on that corresponding execution unit.

The software-pipelining algorithm we rely on is the one implemented by the MMDSP+ C Compiler [5]. It is a modulo software-pipelining algorithm inspired by B.Rau [15]. An engine implements an optimization; it selects loops to be software-pipelined. The selection is based on the following criteria:

**Definition 3.1.** A loop is eligible if it respects the three following properties:

- it does not nest any loop,
- its index runs by 1s,
- it does not contain any i.e-statements.

The last restriction states that the loop body should not contain i.e-statements other than exit tests. Generally, this is a major restriction; developers need to use i.e-statement within a loop body.

In the context of embedded systems, applications are specific: the MMDSP processor is dedicated to the encoding and decoding of sound and video formats e.g. amr, mp3. This kind of algorithm makes intensive use of loops which process huge arrays without any i.e-statements. Note that in a more general case, if-conversion, which can be performed on many predicated VLIWs, greatly lowers the impact of this limitation.

The more instructions can be executed simultaneously, the faster the program will run. The fastest possible execution would be to execute all the instructions of the program in parallel. This is impossible because of the following constraints:

- Data dependency: If instruction A calculates a result that is used as an operand of instruction B, then B cannot execute before A is finished.
- Functional unit: If there are x multipliers (adders, etc) on the chip, then at most x multiplication (addition, etc) instructions can execute at once.
- Instruction unit: The instruction-issue unit can issue at most y instructions at a time.
- Registers: At most z registers can be in use at the same time.

The three last constraints are often lumped together as resource constraints. This is why the software-pipelining optimization is performed at the assembly-level in the compiler. The first constraint, data dependency, is the only one which affects our work. A dependency between two instructions exists if interchanging their order changes the results. A **Data Dependency Graph** — DDG — is used to describe dependencies between instructions: nodes are operations and the set of edges is the set of dependencies. Anti and output dependencies also are respected during scheduling of the loop body.

Overlapping instructions implies in many cases the generation of a prologue and an epilogue to the loop body. Because instructions are overlapped through iterations of the original loop, some instances of instructions may have to be computed beforehand, in the prologue. The same way, the last instances of some instructions may not be computed in the loop body, thus they are moved later, in the epilogue.

3.2 A Practical Example

Freely inspired from A.Appel [4], a source loop is given in figure 2. Originally, it contained array accesses which overcomplicated the reading of the example and do not affect the output. We removed them because they did not change anything to the modulo software pipelining algorithm while they loaded down the notation.

It is a for-loop for which the number of iteration $N$ is unknown at compilation time.

This example is quite complete because it uses all four kinds of data dependency through iterations which can affect the scheduling of instructions. We sum them up in table 1, where indexes represent...
4. SYMBOLIC DEBUGGING OF OPTIMIZED CODE

Debugging optimized code poses two problems [8, 26], the data value problem and the code location problem.

4.1 Data Value Problems

The first problem is known as the set of data value problems. They are the difficulties involved in finding and returning the value of a variable in response to a user’s query.

In order to save registers, some optimizations, thanks to the data flow graph, will make several variables inaccessible at some point in the program. The residency problem occurs when a variable’s value is not accessible. In figure 4, let \( f \) and \( g \) be two functions which have no side effects. Also assume \( x \) is defined within \( f \). The user may request \( x \)’s value whenever the program is running in \( f \). Now assume \( x \) is not used after the 4\textsuperscript{th} line. In order to save resources (registers, memory), the compiler may get rid of \( x \) after the 4\textsuperscript{th} line, i.e. \( x \) is not stored anywhere, it is lost. During a classical debugging session, the user can request \( x \)’s value at the end of \( f \), but in this case of optimization, the debugger cannot give the value back to the user.

```plaintext
1 for (i = 1; i <= N; i++) {
2   a = j + b
3   b = a + f
4   c = e + j
5   d = f + c
6   e = b + d
7   f = 42
8   g = b
9   h = d
10  j = 43
}
```

Figure 2: A for-loop to be software-pipelined

The last subproblem is called the currency problem, see figure 6. The variable \( \text{tmp} \) is not used in the loop, instead, it is used once at line 7, for the same assignment. The compiler may decide to optimize it by using a code sinking or a code hoisting optimization.

Table 1: Variable Dependencies

<table>
<thead>
<tr>
<th>Variable Depends on</th>
<th>Iterations</th>
<th>source line numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_i )</td>
<td>1</td>
<td>(2,4,7,10)</td>
</tr>
<tr>
<td>( j_{i-1} )</td>
<td>2</td>
<td>(3,5,7,10)</td>
</tr>
<tr>
<td>( b_{i-1} )</td>
<td>3</td>
<td>(5,8,2)</td>
</tr>
<tr>
<td>( a_i )</td>
<td>4</td>
<td>(6,9,3,7,10)</td>
</tr>
<tr>
<td>( f_{i-1} )</td>
<td>5</td>
<td>(4,8,2)</td>
</tr>
</tbody>
</table>

Figure 3: Software-pipelined loop schedule

Another subproblem, called the data location problem, occurs when a variable is not located in the expected register or at the expected address. In figure 5, scalarization makes local a global variable by using a temporary variable, here \( \text{tmp} \). Then, in the loop, \( a \) exists somewhere up-to-date, but the debugger will not know its value is located in \( \text{tmp} \). The last subproblem is called the currency problem, see figure 6. The variable \( \text{tmp} \) is not used in the loop, instead, it is used once at line 7, for the same assignment. The compiler may decide to optimize it by using a code sinking or a code hoisting optimization,
the debugging session, the user requests i.e. moving the assignment line 7 before or after the loop. During variable’s value might not be the same at the same point in the one expected by the user. The currency problem arises when a in the loop, but since it has been moved, the value will not be the

Moreover, lines 6 and line 5. APPROACH AND CONTRIBUTION

4.2 Code Location Problem

The second problem is the code location problem. It arises in mapping between locations in the source code and locations in the optimized program.

For instance, dead code elimination generates a one-to-zero relation between the source code and the optimized program, common subexpression elimination generates one-to-many relations, and hardware loops creation generates many-to-one relations.

5. APPROACH AND CONTRIBUTION

We focus hereafter on the problem of debugging software-pipelined loops. Our solution answers this simple question: Given an address and a variable, what is the value of this variable? The code location problem and the data value problem both arise after software-pipelining a loop. For example, figure 7(a) is a very simple while-loop which computes the sum from 0 to MAX-1 (variable \(x\) and the sum of these sums (variable \(y\)). Assume the target processor has 2-issues instructions. The first idea is to parallelize variable initializations at line 1 and 2. At compile time, the loop is rewritten as in figure 7(b). In order to parallelize instruction executions, lines 5 and 7 of the source loop have been copied before the loop entry, and line 6 of the source loop has been copied after the loop body. Moreover, lines 5 and 6 are executed in parallel. So, \(x\) is computed once before entering the loop, and then is computed one iteration step forward \(y\)’s value computation.

4.2.1 Code Location Problem

The code location problem arises when a variable’s value might not be the same at the same point in the source program.

%Code Location Problem Illustration

Suppose the user is debugging this program using a standard tool such as gdb[17]. Suppose also the program stops at address 0x348 in the rewritten code. The debugger gives the hand back to the user stating that it stopped at line 7 in the source code. The user asks for \(y\) and \(i\)’s current values. It seems fair for the user to think that \(y\)’s value corresponds to the current iteration number \(i\). This is incorrect. A trace is given in figure 8, \(y\) equals 4 whereas \(y\) should be 10. When at address 0x348 in the rewritten code \(x\) and \(y\) are computed, \(y\)’s value is one iteration step backward the current iteration \(i\), i.e., \(y\) is computed for the \((i-1)\)th time. This misleads the user about the execution of the program. We would like the debugger to give the current value of the variable and the iteration it corresponds to.

In this paper, we propose a solution for the user not to be misled in such a situation. Our proposal relies on selected information to be generated by the compiler and an algorithm for the debugger not to mislead the user.

**Instance and offset** are two words we need to define in order to remain clear in the rest of this paper.

**Definition 5.1.** An execution of instruction \(S\) is called an instance of \(S\).

We refer to an instance by specifying its occurrence number. The instance number of an operation refers to the source iteration num-

(a) Before Scalarization

```c
int f() {
    int i;
    int x;
    // ...
    a = a + x;
    for (i=0; i<10; ++i) {
        a = a + i;
    }
    // ...
    return 0;
}
```

(b) After Scalarization

```c
int f() {
    int i;
    int x;
    // ...
    tmp = a;
    tmp = tmp + x;
    for (i=0; i<10; ++i) {
        tmp = tmp + i;
    }
    a = tmp;
    // ...
    return 0;
}
```

Figure 5: Data Location Problem Illustration

```c
int f() {
    int i;
    int x;
    // ...
    y = x + y
    i = i + 1
}
```

(a) Source Code

```c
0x334 i = 0
0x338 y = 0
0x33C i = i + 1
0x340 while { i < MAX }
0x344 y = x + y
0x348 i = i + 1
0x34C y = x + y
```

(b) Rewritten Code

Figure 7: Example of Misled Debugging

Suppose the user is debugging this program using a standard tool such as gdb [17]. Suppose also the program stops at address 0x348 in the rewritten code. The debugger gives the hand back to the user stating that it stopped at line 7 in the source code. The user asks for \(y\) and \(i\)’s current values. It seems fair for the user to think that \(y\)’s value corresponds to the current iteration number \(i\). This is incorrect. A trace is given in figure 8, \(y\) equals 4 whereas \(y\) should be 10. When at address 0x348 in the rewritten code \(x\) and \(y\) are computed, \(y\)’s value is one iteration step backward the current iteration \(i\), i.e., \(y\) is computed for the \((i-1)\)th time. This misleads the user about the execution of the program. We would like the debugger to give the current value of the variable and the iteration it corresponds to.

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**Definition 5.1.** An execution of instruction \(S\) is called an instance of \(S\).

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```c
```
Compiling is applying a sequence of optimizations to a program. It can be seen as a composition of functions. Our work tends to focus on one of these functions, this does not mean that any work does not have to be done on other functions i.e. optimizations. A weakness is that property 5.3 can be invalidated by other optimizations (Common Subexpression Elimination Across Iterations —CSEAI— for instance). That is the reason why we try this approach alone first and then as part of a more important work on information propagation through compilation partly based on Adl-Tabatabai [3] and Tice [20].

Even though much work has been done in the field of software pipelining, to our knowledge this is the first attempt to debug software-pipelined loops in a non-transparent manner.

6. DEBUG INFORMATION

As written by Gough, Ledermann and Elms [11], computer programs often need to be examined to determine the cause of apparent errors, or to gain a better understanding of their structure. This examination is called debugging, since its usual objective is the location and removal of program errors (bugs). Compilers such as gcc [16] provide debug information for debuggers via standard debugging information formats e.g. DWARF-2 [1]. Debugging information standards are not usually designed explicitly for debugging optimized code. Compilers do not use every feature which would ameliorate the state of debugging of optimized code in industrial tools (see C.Tice [20]). Without considering any specific debugging information standard, we present in this section information our algorithm needs in order to solve the issue we address.

When a compiler optimizes a piece of code, it knows much more than what it provides as debugging information. A trivial example is the dead code elimination case. When the compiler decides to delete an instruction from the program, it does not record it into debugging information, thus the debugger cannot inform the user when he tries to set a breakpoint at this deleted instruction. When the compiler software-pipelines a loop, it computes the DDG, and so knows where each variable is (or will be) located, computes how many iterations are to be overlapped, as well as other information related to the mapping between the source loop and the software-pipelined loop. During software-pipelining optimization, all such information is mandatory to rewrite the loop into three parts, the prologue, the loop body, and the epilogue. Once the information is known, it becomes straightforward to store it instead of discarding it at the end of the optimization. We instrument the compiler to store some of this information.

For each part of the software-pipelined loop (e.g. figure 3), we instrument the compiler to store four values which informally correspond to boundaries of the loop. We store the lowest and the highest iteration numbers for which instructions are executed in that part and we call them first and last iteration number. Because iterations are overlapped, the highest instance number of instruction of the prologue will very often be higher than the first instance number of instructions of the loop body. This will happen between the loop body and the epilogue as well.

Since each part is made of one block of continuous addresses, we store the first and the last addresses which we call starting and ending addresses. An example of such information is given table 2. The prologue’s first assignment belongs to the first iteration while its last assignment, in terms of instance number, belongs to the fourth iteration. We also store its boundaries, i.e. addresses, here from 0x01 to 0x7. The epilogue’s range of iteration depends on the loop total number of iterations and is here from N-1 to N while its range of address goes from 0x0D to 0x11. Then, we store an integer per instruction: its offset to the current iteration.

```
(gdb) break 7
Breakpoint 1 at 0x33C and 0x348: file loop.c, line 7.
(gdb) run
Starting program
Reading symbols for shared libraries.. done

Breakpoint 1 at loop.c:7
7    i = i + 1;
(gdb) continue 3
Will ignore next 2 crossings of breakpoint 1.
Continuing.

Breakpoint 1 at loop.c:7
7    i = i + 1;
(gdb) print x
x = 6
(gdb) print y
y = 4
```

Figure 8: Example of requesting variables’ values when software-pipelined
7. ALGORITHM

Besides the traditional debug information and the extra information defined previously, debuggers need mechanisms to find their way into this information. In this section, we first clarify our notation system and then describe our algorithm.

7.1 Assumptions and Notations

The algorithm presented here aims at determining precisely for a given variable which source iteration its current value corresponds to. We define structured types, t_part and t_address, which contain information collected during compilation.

The t_address type contains information relative to the three parts of the software-pipelined loop: the prologue, the loop body, and the epilogue. Variables prologue, loopbody and epilogue are used along the algorithm. Access to their information is given with an arrow e.g. prologue->firstIter, see table 4.

The t_address type contains information corresponding to addresses of the object code. Each address denotes an instruction, thus each address assigns to a set of variables, we note this address->setVar. Each operation maps to a source instruction. Because a variable can be assigned only once per instruction at a user-visible level, we use a very simple notation for the access to the line number:lnum corresponding to a variable v of addr->setVar: we write addr->v->lnum and we use the same logic to write addr->v->offset.

Table 2: General Loop Information

<table>
<thead>
<tr>
<th>Source Line Number</th>
<th>Variable Assigned To</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>b</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>c</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>d</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>e</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>f</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>g</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>h</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>j</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3: Instruction Information

<table>
<thead>
<tr>
<th>prologue</th>
<th>loopbody</th>
<th>epilogue</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>(N-1)</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>0</td>
</tr>
<tr>
<td>0x01</td>
<td>0x09</td>
<td>0x00</td>
</tr>
<tr>
<td>0x07</td>
<td>0x0B</td>
<td>0x11</td>
</tr>
</tbody>
</table>

Table 4: Structures Used

```
<table>
<thead>
<tr>
<th>Type Name</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_address</td>
<td>-&gt; setVar</td>
</tr>
<tr>
<td>t_address-&gt;v</td>
<td>-&gt; lnum</td>
</tr>
<tr>
<td>t_address</td>
<td>-&gt; offset</td>
</tr>
<tr>
<td>t_part</td>
<td>-&gt; firstIter</td>
</tr>
<tr>
<td>t_part</td>
<td>-&gt; lastIter</td>
</tr>
<tr>
<td>t_part</td>
<td>-&gt; startAddr</td>
</tr>
<tr>
<td>t_part</td>
<td>-&gt; endIter</td>
</tr>
</tbody>
</table>
```

Table 5: Input Variables

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Type</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ba</td>
<td>t_address</td>
<td>breaking address</td>
</tr>
<tr>
<td>i</td>
<td>integer</td>
<td>The iteration number</td>
</tr>
<tr>
<td>rv</td>
<td>t_variable</td>
<td>requested variable</td>
</tr>
<tr>
<td>prologue</td>
<td>t_part</td>
<td>prologue</td>
</tr>
<tr>
<td>loopbody</td>
<td>t_part</td>
<td>loop body</td>
</tr>
<tr>
<td>epilogue</td>
<td>t_part</td>
<td>epilogue</td>
</tr>
</tbody>
</table>

Table 6: Output Variables

The breaking address of type t_address is noted ba. For instance, if the requested variable is assigned to at the breaking address, we use the following notation: rv ∈ ba->setVar. Table 4 sums up the data structures and notations used in our algorithm. Table 5 sums up the input variables for the algorithm. Table 6 shows the result format of the algorithm. We also use a temporary address named tmpAddr of type t_address.

```
1  ask_value (t_address ba, t_variable rv) {
2    if (ba ∈ prologue) then
3      // see figure 10
4    else if (ba ∈ loopbody) then
5      // see figure 11
6    else if (ba ∈ epilogue) then
7      // see figure 12
8    else
9      // ba is not set in the loop.
10  }
```

Figure 9: General Algorithm

7.2 Pseudo-code

In this section, we give the algorithm in pseudo-code. It helps the debugger to answer the original question: At a given address and for a given variable, what is the value of this variable? The breaking address ba can be in the prologue, in the loop body or in the epilogue. We present 3 sub-algorithms, one for each case. The entire algorithm in figure 9 could be written more effectively, but we chose to divide it into three parts in order to make it clear to the reader.

7.2.1 Prologue

When ba is in the prologue, we first look backward for the last address assigned rv. We then look for the number of times it has been assigned to by this operation. Checking the line number and not only the variable allows a variable to be assigned more than once in the loop body.
7.2.2 Loop Body

If ba is in the loop body, we have to look for the address assigned to rv in a slightly different manner. Indeed, if the break occurred during the first iteration of the loop body, then it might be an address assigned from the end, not from the beginning.

Once we know where rv has been assigned, thanks to the offset, we can tell in which iteration it occurred.

7.2.3 Epilogue

The epilogue is very similar to the prologue, except that we count the number of times rv has been assigned from the end, not from the beginning.

if (i ≤ loopbody->startIter) then
  tmpAddr = ba - 1
  while (tmpAddr ≥ prologue->startAddr)
    ∧ (rv ∉ tmpAddr->setVar)
    do
      // search backward for rv
      tmpAddr = tmpAddr - 1
    if (rv ∉ tmpAddr->setVar) then
      result->addr = null
      ∧ (tmpAddr->rv->lnum == assAddr->rv->lnum)
      then
        result->inst++
      tmpAddr = tmpAddr + 1
  Figure 10: ba is in prologue

else
  tmpAddr = ba - 1
  while (tmpAddr ≥ prologue->startAddr)
    ∧ (rv ∉ tmpAddr->setVar)
    do
      // search backward for rv
      tmpAddr = tmpAddr - 1
    if (rv ∉ tmpAddr->setVar) then
      result->addr = null
      ∧ (tmpAddr->rv->lnum == assAddr->rv->lnum)
      then
        result->inst++
      tmpAddr = tmpAddr + 1
  if assAddr > ba then
    result->inst = i + assAddr->rv->offset
  else
    result->inst = i - 1 + assAddr->rv->offset
  Figure 11: ba is in loopbody

8. EXPERIMENTATION CONTEXT

8.1 Tool Framework

Our experimentation is done with a tool framework [14] including a compiler, MMDSP+ C Compiler, a debugger, MMDSP+ GDB, and a set of specific applications.

MMDSP+ C Compiler is a compiler for an embedded processor called MMDSP [5]. It performs state-of-the-art optimizations. It has been designed with a modular framework allowing the development and integration of new optimizers both high and low level [5]. Its architecture is represented in figure 1. It is built around the CoSy compiler development suite [2]. The in-house back-end, named EliXir, is an STMicroelectronics proprietary back-end designed to replace CoSy back-end optimizers (e.g. the scheduler and register allocator) with a more modular infrastructure allowing more aggressive low-level optimizations (e.g. software-pipelining, peephole, post addressing mode). The structure of EliXir is represented in figure 13.

MMDSP+ GDB is based on the GNU Source-Level Debugger gdb [17]. It uses GDB/MI protocol to communicate with Eclipse.

1http://www.eclipse.org/
It has been adapted to handle gracefully the 24 bits memory of the
MMDSP. It also handles circular pointers and the dynamic 16/24
bits arithmetic mode of the processor.

The set of applications contains several audio codecs such as the
Enhanced Full Rate (EFR) codec of the GSM wireless communi-
cation standard, g723.1, mp3 and AMR codecs. 80% of the code is
made of loops; mmdspcc performs software-pipelining on 30% to
50% of these loops, depending on the codec.

8.2 Experiment
To validate our approach, we divided our experiment into two
steps. In the first step, we implemented and validated the approach
presented in this paper with every other optimization turned off.
In the second step, we instrumented selected engines of compiler
so they kept up-to-date debugging information before and after the
software-pipelining engine.

1st Step-The first step is fully described in the present paper.
Our instrumentation stores values previously computed by the orig-
inal algorithm, hence it is less than 100 lines of code. We have
extended the debugger with approximately 900 lines of code: re-
quested variables’ values are now given with a context of execution,
see figure 14. This example is written in a gdb-like syntax.

(gdb) break 7
Breakpoint 1 at 0x33C and 0x348: file loop.c, line 7.
(gdb) run
Starting program
Reading symbols for shared libraries . done
Breakpoint 1 at loop.c:7
7   i = i + 1;
WARNING: software-pipelined loop:
2 iterations overlapped
(gdb) continue 2
Will ignore next 2 crossings of breakpoint 1.
Continuing.
Breakpoint 1 at loop.c:7
7   i = i + 1;
WARNING: software-pipelined loop:
2 iterations overlapped
(gdb) print x
   x = 6
WARNING: software-pipelined loop:
   accurate for iteration (i == 3)
(gdb) print y
   y = 4
WARNING: software-pipelined loop:
   accurate for iteration (i == 2)

Figure 14: For an example corresponding to the debugging of pro-
gram in figure 7(a). This example follows the same steps of exec-
uction as example in figure 7. A breakpoint is set at line 7 and the
program runs until reaching it.

2nd Step-The second step is not described in this paper, we shall
only give a brief description. Our algorithm supposes debugging
information to be accurate before running the software-pipelining
engine. In order to respect this assumption, we have instrumented
MMDSPl+ C Compiler so other engines maintain information up-
to-date during compilation. We have followed a non-transparent
approach. Labeling instructions through optimizations allows the
debugger to map target instructions with source statements even
though the source code has been highly optimized.

We restricted our field of investigation to four engines: dead
code elimination, common subexpression elimination (CSE), hard-
ware loop creation and miscellaneous code motions such as code
sinking and code hoisting. Since we had to write a library to ma-
nipulate information in the previous step, the instrumentation cor-
responds to approximately 1400 lines of codes and less than 100
lines of code for each engine. The set of selected optimizations is
relevant because it covers every kind of modification optimiza-
tions can perform to the code: elimination (dead code elimination),
duplication, rewriting (CSE, hardware loop creation), reordering
(misc. code motions). It also includes modifications made to
the instructions instances order and not only to instructions (see
C.Jaramillo [13]).

So far, our implementation did not show any dysfunctions. No-

tice that there is not any relevant metric to demonstrate the validity
of our approach because a non-transparent debugger relies on the
user. The size of debugging information added to the binary file is
not a significant information and the time needed by the debugger
to load it is negligible.

9. PREVIOUS WORK
To the best of our knowledge, debugging software-pipelined loops
has never been addressed non-intrusively or without specific hard-
ware mechanisms.

John Hennessy [12] was the first to define notions of non-current
variables and endangered variables. If an optimized program aborts
or a debugger stops the program, the resulting value of the variable
may not equal the value of the variable in the original source pro-
gram at the corresponding point, and is called non-current. A var-
iable is called endangered when its dependency on the path
taken. Hennessy’s ideas have served as the foundation for much of
the research done in this area. Wall, Srivastava, and Templin [21]
and Copperman and McDowell [7] later revised Hennessy’s origi-

al algorithms to correct for changes in compiler technology that
invalidated some of Hennessy’s original assumptions.

Polle T. Zellweger [26, 25] focused on two optimizations: cross-
jumping, an optimization which consists in replacing a portion of
code by a function call, and inlining, an optimization which con-
sists in replacing a function call by a copy of the function itself.
The solution she proposed did not address the debugging of software
pipelined loops or instruction scheduling, but she gave original def-

initions for transparent behavior, and correct, or non-transparent
behavior. Indeed, a debugger is said to have a transparent behavior
when its responses to user requests concerning the execution of an
optimized program are the same as responses would be for an unop-
timized version of the program. A debugger is non-transparent, or
correct, when it can display, in source program terms, the relevant
changes caused by optimization at execution point

Coutant, Meloy and Ruscetta proposed what they called A Prac-
tical Approach To Source-Level Debugging of Globally Optimized
Code [8]. Their tool, DOC, is a prototype of the existing C com-

piler and source-level debugger for HP900 Series 800 which deals
almost exclusively with the data value problem caused by optimiza-
tions. Their solution partially solves the data value problem trying
to remain consistent with the user’s perception of the source, i.e.
they try to recover variables values.

Brooks, Hansen and Simmons’ work [6] aims at providing a vi-

sual feedback during the debugging of optimized code. They de-
signed the Convex debugger, CXdb. It follows a non-transparent
approach: it highlights various expressions within the source state-
ments as the corresponding instructions are executed. No expla-
nation is provided to the user, thus, unless the latter knows which
optimizations might have been performed, it can become very def-
ficult to determine what happened, and hence understand the con-
text. While they solved the location problem, they only partially
addressed data value problems. A resident variable is implicitly
Roland Wismüller [22] proposed an algorithm for solving the currency problem. Based on data flow analysis, his solution determines whether a variable’s value is current or not, but no solution is provided to recover any value. His algorithm is based on a comparison of two data flow graphs. They both are unrolled in order to make the difference between two instances of the same instruction. The same unrolling technique has been used by Dhamdhere and Sankaranarayanan [9]. Wismüller is also the first to use a mapping which uses semantically equivalent instructions, what C.Tice will later call key instructions [18].

J.Gough, J.Ledermann and K.ELms [11] described an alternative model in which any needed information is extracted by coopting a modified version of the compiler during the debugging session. They do not explicitly solve the code location problem nor do they solve data value problems. Three years later, K.ELms [10] released a more detailed implementation.

Ali-Reza Adl-Tabatabai [3] addressed the code location problem and data problems for a given set of scalar optimizations. His code location problem solution relies on a dual labeling method and expects breakpoints and exceptions to happen in the expected order if instructions are not scheduled. In order to track modification brought to statements, the compiler maintains two mappings: the object-to-source mapping and the source-to-object mapping. As stated in his conclusions [3, page 171], he does not address the debugging of software-pipelined loops.

Le-Chen Wu and Wen-Mei W.Hwu [23, 24] address the code location problem from the user’s point of view. They proposed an implementation scheme for setting breakpoints. They implemented their technique by modifying an existing compiler and running tests with it. They concluded that their scheme was unable to handle loop transformations which reordered instructions from different iterations of the original loop in the same iteration of the new loop (software pipelining, for instance).

D.M.Dhamdhere and K.V.Sankaranarayanan [9] presented a partial solution to the data value problem. Their proposal is based on a neat reduction of the data flow graph into a list of nodes ordered according to the time when their last occurrence was executed. The data flow graph is unrolled and then reduced to a list. To do so, they used the Zellweger’s time-stamp idea [26] and proved the equivalence of the two graphs under hypothesis of restriction. They concluded that their proposal is a practical basis for providing partially transparent debugging.

Caroline Tice’s approach to the problem is based on the idea that programmers may want to know what happened to their code during optimizations [20]. She developed a tool, OPTVIEW [19], which displays parts of optimizations to the user. Her tool displays a modified version of the source code, with comments added whenever possible. Her main contribution is the key instruction concept which allows the debugger to set source-level breakpoints. In order for this mechanism to be accurate, for each source statement she defines which instruction embodies most closely that statement’s semantics. For example, the key instruction for an assignment statement is the one that stores the assignment value either to the variable’s location in memory, or to a register (if the write to memory has been eliminated). The key instruction for a function call is the jump to the code for that function. She also addresses the eviction recovery of wandering data by modifying Coutant, Meloy and Ruscetta paper’s scheme of variable range table. She proposed setting hidden breakpoints to recover data, but only in subroutines where the user already had set breakpoints in order to minimize the slow down of execution. In her conclusions [20], she considers the limitations to her work especially as it applies to loop transformations. She provides a summary of user feedback, but her tool is not available for experimentation.

C.Jaramillo [13] proposed a fully transparent solution to symbolic debugging of optimized code. Her main goal is to hide every single transformation from the user by making heavy use of hidden breakpoints and tables such as reportable variables table, overwritten variables table, range table, and many others. As a result, it seems to drastically slow down the program execution during the debugging session. We believe it is a major showstopper to industrial usage of these techniques.

10. CONCLUSION AND FURTHER WORK

This paper addresses the non-transparent debugging of software-pipelined loops. We proposed an algorithm for the debugger to reveal non-transparently the program’s behavior using information stored by the compiler while software-pipelining a program. This approach only depends on the scheduling algorithm and not on the processor. We also presented our experimentation context based on an embedded system processor: the MMDS which implements a modulo-software-pipelining algorithm. To the best of our knowledge, this problem has never been addressed before. Our development framework prototype needs the developer to already know a bit about compilation optimizations. This may be seen as a disadvantage while it actually is our intention not to hide details to the programmer. The embedded developers who will be our tool’s first class users usually have sufficient knowledge of their systems to understand the additional information we provide.

As further work, we will extend our method to other software-pipelining algorithms, so that compilers which implement them could be extended as well. The cornerstone of this work will be showing that the algorithm respects property 5.3.

Another further work would be trying to adapt our algorithm to a transparent debugging of software-pipelined loops. This would be the exact opposite approach to the one adopted here. Using invisible breakpoints, slicing techniques, and pools to store values are promising ideas, and many papers on the subject of transparent debugging are built on them.

11. ACKNOWLEDGMENTS

The authors would like to thank Vincent Lorquet, Quentin Clombet, Vincent Colin-de-Verdière, Jean-Marc Daveau and Thierry Lepley from the CEC team for their help during our experiments. The authors would also like to thank Laurent Gérard and Denis Pilat from the IDTEC Team for their helpful comments.

12. REFERENCES


