Application of Abstract Interpretation to the Automotive Electronic Control System

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Abstract. The verification and validation of industrial automotive systems is increasingly challenging as they become larger and more complex. Recent automotive Electric Control Units (ECUs) have approximately one half to one million of lines of code, and a modern automobile can contain hundreds of controllers. Significant work-hours are needed to understand and manage systems of this level of complexity. One particular challenge is understanding the changes to the software across development phases and revisions. To this end, we present a code dependency analysis tool that enhances designer understanding. It combines abstract interpretation and graph based data analysis to generate visualized dependency graphs on demand to support designer's understanding of the code. We demonstrate its value by presenting dependency graph visuals for an industrial application, and report results showing significant reduction of work-hours and enhancement of the ability to understand the software.

1 Introduction

In recent years, functional requirements for automotive control systems have become far more sophisticated. This necessitated the development of more complex and larger scale control software, which lead to a significant increase in work-hours. Fig 1 shows the amount of work-hours for control software development based on our project management data, which reveals that work hours almost doubled from 2012 to 2017. Based on this trend, the work-hours are expected to increase considerably in the near future.

One of the causes of the considerable increase in work-hours is that much time is spent understanding complex vehicle systems that are composed of many smaller subsystems, which we call *unit-systems*. The designer's interests are to grasp the vehicle system architecture, the unit-system architecture, and the impact of their revisions or extensions at the program level. Therefore, accurate and comprehensive visualization of abstractions of the software will help to increase the designer's understanding and will mitigate the increase in work-hours.

In this paper, we present a tool that provides various view graphs that can support the designer's understanding of the system by using a static analysis technology. Characteristics of our tool include the following: (1) ability to control the scalability and preciseness based on the designer's interest, and (2) a guarantee of soundness (there are no missed dependencies). Traditional code analysis does not guarantee absolute precision. On the other hand, legacy static analysis guarantees precision but is not scalable. Thus we developed an abstract interpretation technology, which is based on static analysis methods, to our tool. In addition, a graph-based data base is exploited to manage enormous dependency for large scale code.

Specific contributions of the paper are:

- Explaining background on automotive control system software and the corresponding industrial challenges that the support the designer's understanding to maintains our product quality under situation of increasing work-hours trend. (Section 2)
- Algorithmic and implementation innovations needed for scalable and precise abstract interpretation (Section 3)
- An overview of the C Analysis Tool (CAT) developed (Section 4).
- Results of the application of our tool to the actual control system code (Section 5).

2 The Challenges of Modern Automotive Software

2.1 Architecture of Automotive Software

Figure 3 shows the software architecture of a modern vehicle. The vehicle system consists of several unit-systems, like the engine and the transmission, which have their own ECU; each ECU communicates via a CAN network. The majority of ECUs are implemented in C. The largest unit-system in the vehicle is the engine ECU, and we use it as a recurring example. The engine ECU has multiple features, such as ignition, injection, and variable valve control. Each feature contains program modules that are divided into functional units, each of which are collections of several functions. The functions that compose the modules are allocated to tasks for the Operating System (OS), which manages time driven and event driven tasks.

A key characteristic of the software is the scale; each ECU has up to half a million of lines of code (LoC). Several thousand global variables are used for inter-function communication, which results in module interdependency and a high level of code complexity. Pointer access is used as little as possible in the application layer, but many pointer accesses occur at the lower layer, like for

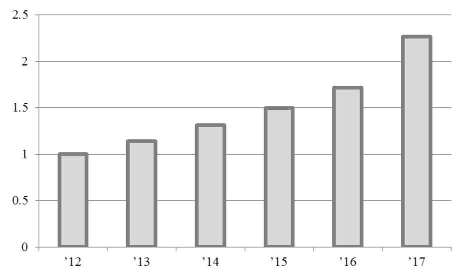


Fig. 1. Magnification of work-hour based on 2012.

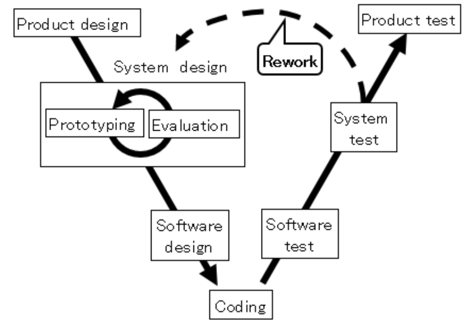


Fig. 2. Design development of automotive software development.

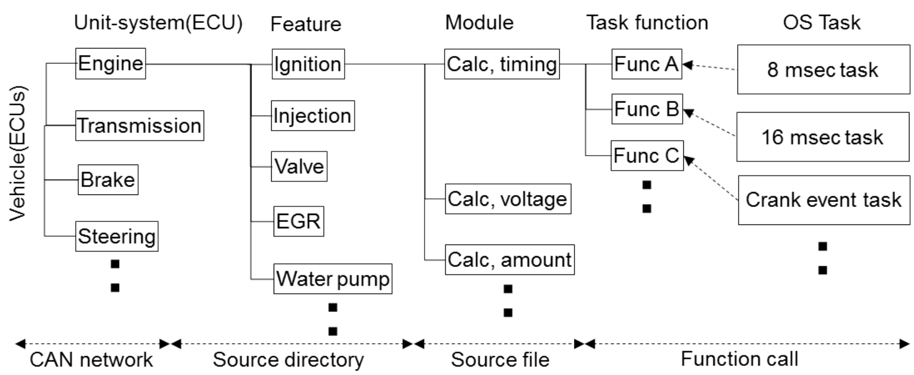


Fig. 3. Architecture of automotive control system.

sensor data, or ROM (Read Only Memory)/RAM (Random Access Memory) access. About five hundred such pointers are used in the lower layer.

2.2 Development Process

Figure 2 shows the automotive software development process for the Electronic Control Unit (ECU). Our process uses a version of the typical V-model design process. Since complex physical phenomena, such as the vehicle dynamics, are the target of the control algorithms, prototypes of the physical components are used to develop system software. The prototype development tends to be incremental, focused on components, while re-using, and extending legacy systems. The system design involves iterative development of the prototype, along with evaluation, while validating operation of the control system in actual usage environments. Due to the use of iterative prototypes and corresponding control algorithms, a spiral-up type process is incorporated into the system design process on the left side of the V-model.

Our development process involves various testing activities that are applied on the right side of V-model. Those tests include evaluation of the software on actual vehicles, engine test beds, HILS (Hardware-in-the-Loop-Simulation), and SILS (Simulation-in-the-Loop-Simulation). Those tests are more intense (demanding, in terms of system performance) and exhaustive than the evaluation at the system design phase and are employed to achieve and maintain quality up to the final product test phase.

A main source of inefficiency in our process is the rework involved to return to an earlier phase of the development process, in the left side of V-model, from a test process, in the right side of V-model. The most costly rework occurs when returning to the system design phase from the system test phase, due to the many development and testing steps that have already been performed to reach the testing phase. Thus making well defined system designs is important to reduce the amount of rework. In that sense, misunderstanding the system design is one of the significant causes of the rework. Accordingly, a good review process, founded on a firm understanding of the implementation, is required to help limit the amount of rework.

The designer will benefit from the following, either for a new development or for extending an existing system design.

1. Understanding the software architecture: It is important to decide which module or function should be revised beforehand. In that sense, the developer needs to understand the entirety of the program architecture on every level, such as the function, the module, the sub-system, and the system levels.
2. Impact analysis of the revised variables or the calibration parameters: The designer is interested in what kind of influence their own design revision has to the system. The impact analysis is necessary in the Design Review Based on Failure Mode (DRBFM) [1] to prevent the revision leading to unexpected behaviors when revising variables or re-calibration of parameters.

The review process is basically done in manual or semi-manual manner, such as reading a natural language of the specification or using the `grep` command in for C code. When considering the module or function level graph, this process can be sufficient, since the scale is small. However, if the system level graph is considered, the manual process becomes a development bottleneck, because the system scale is large, and the corresponding system graph is created manually.

2.3 Technical Issue and Approach

In order to automate the software architecture analysis and impact analysis, we present a method based on static analysis. The required functionality and challenges are as follows.

Dependency Analysis To understand the ECU program architecture, we need to generate the "unit-system dependency graph" by using exhaustive dependency analysis in the reviewing phase. This is like a map for software architecture, which aids in understanding the software. The software directory composition, shown in Fig. 3, is not sufficient because it does not contain essential program information like function calls or global variable

Program 1. Code example for struct/union.

```
1  struct st {
2    int m1;
3    int m2;
4  };
5
6  extern int g_in;
7  struct st g_st;
8  int g_out1, g_out2, g_out3;
9
10 void main(void){
11   if (g_in == 1)
12     g_st.m1 ++;
13
14   if (g_in == 2)
15     g_st.m2 ++;
16
17   g_out1 = g_st.m1;
18   g_out2 = g_st.m2;
19   g_out3 = g_st.m1 + g_st.m2;
20 }
```

Program 2. Code example for closed loop.

```
1  extern int g_in1;
2  extern int g_in2;
3  int g_x1;
4  int g_x2;
5
6  void main(void) {
7    if (g_in1)
8      g_x2 = 0;
9
10   g_x1 = g_x2;
11
12   if (g_in2)
13     g_x2 = g_x1;
14 }
```

reads/writes; program (Control and Data) dependencies are needed to make a more helpful graph [2]. Particular challenges are;

1. The analysis must scale to a half million lines of code and handle several thousand global variable.
2. At some levels of detail we require precise handling of nested struct and union variables. These often contain flags indicates important conditions, like whether the engine is idling or whether the engine is in a fuel-cut mode. Program 1 shows an example. It has `struct st` on L1 and the members are accessed in `main` function several times.
3. It is necessary to consider the software as a closed-loop system. In that case, the entry function is called repeatedly in the embedded controller; therefore, it is necessary to consider the previous status of global variables. Program 2 shows an example. When `main` on L6 is called repeatedly for the closed-loop system, 2nd call of L10 depends 1st call of L13 in specific case. We call this capability the periodic option, which is an option for our data dependency analysis.

Pointer Resolution The dependency analysis must be able to handle both data and function pointers. Pointer analysis is challenging in general, but this functionality is a key requirement for static analysis tools and means that purely syntactic approaches to dependency analysis will not work. False negatives for pointer analysis are not allowed, because it results in missing important cases. We require flow, loop, array, and struct/union awareness. Program 3 is an example demonstrating the variable pointer use-case. It has array on L2-4, and loop on L10, furthermore pointer accesses on L7 and L8. Program 4 demonstrates the function pointer use-case. It has function pointer on L20, and arrow access by using function pointer “p” on L21.

A designer can typically resolve a pointer manually within 15 minutes. Usually, the designer manually resolves only what they deem interesting, which usually exists at the module level. However, if the vehicle or system graph

Program 3. Code example for pointer.

```
#define ARRAY_SIZE  4
const int cAarray[ARRAY_SIZE] = { 10, 20, 30, 40};
int gArray1[ARRAY_SIZE];
int gArray2[ARRAY_SIZE];

void main(){
  const int* p0 = cAarray;
  int* p1 = gArray1;

  for (int i=0; i<ARRAY_SIZE; i++){
    *p1 = cAarray[i];
    gArray2[i] = *p0;
    p0++;
    p1++;
  }
}
```

Program 4. Code example for function pointer.

```
struct st {
    int (*req)(char, char *);
};

int f1( char, char *);
int f2( char, char *);
const struct st fptbl1[]={
  { f1 },
  { f2 },
};

int g1(char, void*);
int g2(char, void*);
int (* const fptbl2[])(char, void *) = {
  g1,
  g2,
};

void func(int id, int len, char* buf ){
   const struct st *p = &fptbl1[id];
    p->req(len, buf);
}
```

is considered in an initial phase of development, all pointers should be resolved to clarify all dependency. In this case, the work hours are estimated at about 125 h (=15 min * 500 pointers). This is an unreasonable amount of work-hours to spend resolving pointers.

The embedded ECU does not have un-resolvable pointers because it is a safety critical system and does not use dynamic memory allocation. Even considering pointers in loop statements, there are no unbounded loops because the number of loops are based on constant values, like the number of banks, cylinders, and the look-up table size.

Program Slicing We attempt to apply program slicing [3] to the "unit-system dependency graph" for the impact analysis. This is similar to a path-planning problem. Often the generated graphs are too large to understand. To address that, we expect a kind of extraction functionality that allows the designer to focus on their interests. Program slicing is a kind of forward and backward analysis on dependency. Our expected use-case is impact analysis from the revised variables or the calibration parameters to understand the influence of their revisions. The challenging aspect is to handle enormous dependency from a half million lines of code and on-demand access for forward and backward analysis.

As many of these challenges require understanding parts of the semantics of the program, purely syntactic approaches to the dependency graph are not sufficient. To this end, we use abstract interpretation, which can produce scalable and precise results and further guarantee soundness regarding pointer and dependency analysis. To support the enormous information management on the slicing requirements, we use a non-relational database. In the next section, we describe the key technique: abstract interpretation.

3 Abstract Interpretation

Abstract Interpretation [4] is a mathematical framework for designing, developing and understanding static analysis techniques [5]. It provides general results, based on order theory, that guarantee soundness and termination of an analysis given a few basic properties of the data structures and functions used. These allow the development of a new analysis to be reduced to developing one data structure and two (optionally three) functions:

Domain A domain is a mathematical object that *represents* a set of possible program states. The conventional approach to implementing abstract interpretation analyses to create a data-structure for the domain. Commonly this is a *non-relational* domain, a map from variable to an abstract representation of their possible values (for example intervals, or sets of dependencies).

Transform A function that takes the domain representing the state before an instruction and generates the domain representing the possible program states after. This is the abstract version of executing one step of the program. The transform function covering all possibilities (in this case, tracking all dependencies) is one of the key criteria for a sound analysis. Obviously the details of transformation will depend on the domain, for example, if the domain uses intervals then the transform function will perform interval arithmetic.

Merge A function that takes two domains and combines them into one that includes things represented by either (but may contain more). In the case of intervals, this would be merging the two intervals. Merge is the over-approximate version of a union and allows control-flow paths to be merged, a key criteria for termination.

Widen A key result in abstract interpretation is that the fixed-point of an (over-)approximation is an (over-)approximation of a fixed-point. So just by iterating the analysis, loops can be handled in a correct and terminating manner. Depending on the domain, direct iteration can take too long, so a widening function is often used to accelerate the process. In the case of intervals this might be setting the upper or lower bounds to their max.

3.1 Variable-Sensitivity Domain

As this project needs to compute dependencies for each variable individually and does not need to track the relationships between them, it is sufficient to use a non-relational domain. This means that we can represent the state of a program a given location using one map which stores an object for each variable. Doing so allows us a uniform and simple way of handling one of the requirements – a variable level of sensitivity in the analysis depending on whether it is being analyses at feature, module or task function level.

By implementing a common object interface, we can use dynamic dispatch to control the objects, and thus the precision, used to track arrays, pointers, structs, unions and combinations of them. When the program is analysed at the large scale, we can smash arrays, tracking one dependency set per arrays, and switch seamlessly to per-element dependencies at smaller scales. Similarly, we can switch from just dependencies to tracking constant value or intervals for each variable as well to increase precision for more detailed analyses.

Although this approach is less general than conventional approaches using separate value, array and pointer analyses and reduced products or open combinations [14], it scales better and handles large, complex, global data-structures (for example, pointers to arrays that are members of structs) in a clean and simple manner. It also simplifies various implementation and algorithmic improvements discussed below.

3.2 Copy-on-Write Data Structures

As we need to generate dependencies for every location in the program and keep these in memory to handle periodic analysis as described above, memory is a significant concern. If we are to store 1,000,000 domains (one per line of code), each tracking up to 10,000 variables (not counting per-element analysis of arrays), then every byte required by a dependency set will need 10 GB of RAM.

Here the "one big map" approach of the variable sensitivity domain is of great use. Although we have to store domains for every program location, the majority of them are largely similar to the domains at preceding locations. By using a custom copy-on-write map data-structure, we only have to store the *difference* between two domains, which makes the memory consumption tractable. The authors believe a similar approach is implemented in Astrée [15] although the details are not public. This also gives a fast way of iterating across the differences between two domains.

3.3 Three-Way Merge

Conventional abstract interpretation is *context-insensitive*, so each call to a function will merge the calling state with the starting state of the function. For programs with fixed and tight scoping rules, this is not necessarily a problem. However when handling a large number of global variables it causes an interesting problem.

Program 5. The need for three way merging

```
int gState;

void func (void) {
  // Does not modify gState
}

void task(void) {
  gState = INIT;
  func();

  // Other functionality

  gState = FINAL;
  func();
}
```

Consider the program in Program 5. The first call to `func` will correctly track the dependencies and the constant value of `gState`. The second call to func will merge in its value of `gState` which causes a problem on function return : even though the function does not alter `gState` its value and dependencies will be set to the merge of *all possible calling locations*. In the case of low-level utility functions this can cause very significant loss of precision, particularly when unwinding loops.

To avoid this problem without the cost of performing full context-sensitive analysis, we use the dependencies and modification information implicitly stored in the copy-on-write data structures. On function return, rather than just merging the state at the end of the callee into the caller, we identify each of the variables (array elements, struct fields, etc. depending on the sensitivity) that has changed *between the start and end of the callee* and merge only those into the caller state, resulting in a three-way merge.

4 C Analysis Tool

Figure 4 shows the C Analysis Tool (CAT) architecture. The CAT basically consists of three components. The CPROVER [7] component compiles ECU code and executes the abstract interpretation and finally outputs the instruction level of dependency. The Orient-DB [8] component is a non-relational database and deals with the enormous dependency information and analyzes forward and backward analysis based on the dependency on demand to implement the slicing. The visualization component converts instruction-level of dependency to a more user-friendly level. The visualization back-ends can be accessed via a Java-API, and the user can operate it from their own environment or an Integrated Development Environment (IDE) like MATLAB ®, Eclispe ®, Visual Studio ®, Windows ®CMD and so on. Those components are explained in detail in following sections.

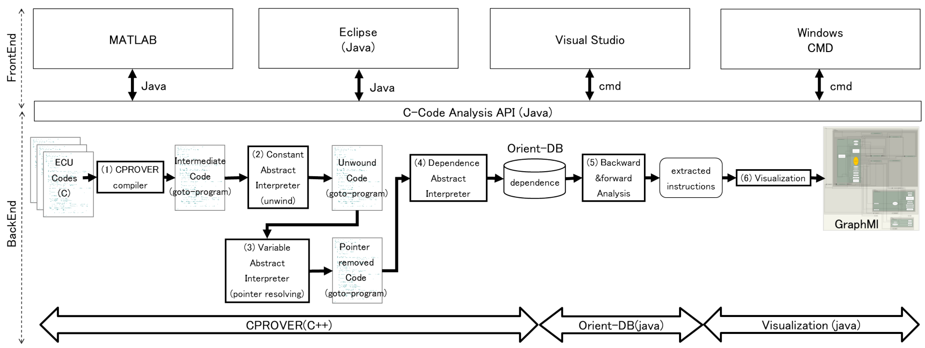


Fig. 4. C Analysis Tool architecture.

4.1 CPROVER

CPROVER [7] is an open-source C++ framework for building C, C++ and Java analysis and verification tools. It provides components for compilation, program transformation and analysis, abstract interpretation, symbolic execution and SMT solving. For instance, C Bounded Model Checker (CBMC) [9] is a well-known bounded model checker and is implemented using CPROVER.

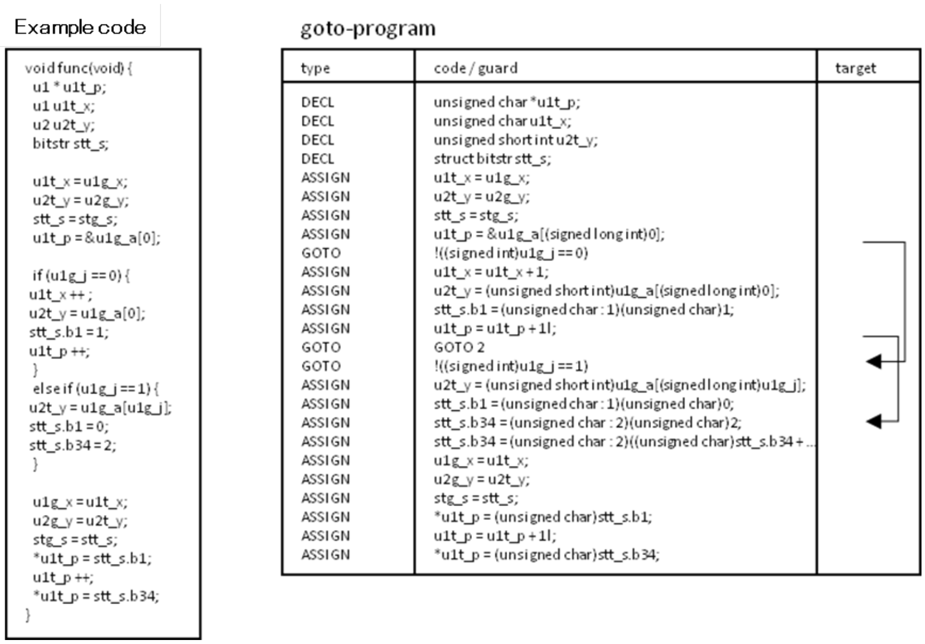
`goto-cc` CPROVER has a compiler `goto-cc` which supports `gcc` [10] equivalent compiler options. This means `goto-cc` can compile C-code by just changing the command `gcc` to `goto-cc` in a make-file, which has a high advantage in industrial application. The `goto-cc` produces a "goto-program", which is a kind of intermediate representation (see Fig. 5). In our CAT tool, the `goto-cc` is used in **CPROVER compiler** ((1) in Fig. 4).

`goto-analyzer` is the abstract interpreter from CPROVER. It operates on goto-programs and thus is language independent. The `goto-analyzer` supports three types of abstract domain, which are the constant domain, the variable sensitivity domain, and the dependency domain.

Constant Domain ((2) in Fig. 4): Finds unwinding-bounds for the loops, then it unwinds the original code. The command is `goto-analyzer --constant`

Variable Domain ((3) in Fig. 4): Simplifies and removes the data and function pointers with array and struct/union awareness. The command is `goto-analyzer --variable --structs --arrays`

Dependency Domain ((4) in Fig. 4): Extracts the instruction level dependency from the pointer-resolved goto-program. It supports typical control dependency and data dependency with array and struct/union awareness. In addition, it supports the recurrent data dependency, which is an embedded specific option. Typically, the embedded controller calls a task repeatedly


Example code

```
void func(void) {
  u1 * u1t_p;
  u1 u1t_x;
  u2 u2t_y;
  bitstr stt_s;

  u1t_x = u1g_x;
  u2t_y = u2g_y;
  stt_s = stg_s;
  u1t_p = &u1g_a[0];

  if (u1g_j == 0) {
 u1t_x ++ ;
 u2t_y = u1g_a[0];
 stt_s.b1 = 1;
 u1t_p ++;
  }
  else if (u1g_j == 1) {
 u2t_y = u1g_a[u1g_j];
 stt_s.b1 = 0;
 stt_s.b34 = 2;
  }

  u1g_x = u1t_x;
  u2g_y = u2t_y;
  stg_s = stt_s;
  *u1t_p = stt_s.b1;
  u1t_p ++;
  *u1t_p = stt_s.b34;
}
```

goto-program

type	code / guard	target
DECL	unsigned char *u1t_p;	
DECL	unsigned char u1t_x;	
DECL	unsigned short int u2t_y;	
DECL	struct bitstr stt_s;	
ASSIGN	u1t_x = u1g_x;	
ASSIGN	u2t_y = u2g_y;	
ASSIGN	stt_s = stg_s;	
ASSIGN	u1t_p = &u1g_a[(signed long int)0];	
GOTO	!((signed int)u1g_j == 0)	
ASSIGN	u1t_x = u1t_x + 1;	
ASSIGN	u2t_y = (unsigned short int)u1g_a[(signed long int)0];	
ASSIGN	stt_s.b1 = (unsigned char : 1)(unsigned char)1;	
ASSIGN	u1t_p = u1t_p + 1l;	
GOTO	GOTO 2	
GOTO	!((signed int)u1g_j == 1)	
ASSIGN	u2t_y = (unsigned short int)u1g_a[(signed long int)u1g_j];	
ASSIGN	stt_s.b1 = (unsigned char : 1)(unsigned char)0;	
ASSIGN	stt_s.b34 = (unsigned char : 2)(unsigned char)2;	
ASSIGN	stt_s.b34 = (unsigned char : 2)((unsigned char)stt_s.b34 + ...	
ASSIGN	u1g_x = u1t_x;	
ASSIGN	u2g_y = u2t_y;	
ASSIGN	stg_s = stt_s;	
ASSIGN	*u1t_p = (unsigned char)stt_s.b1;	
ASSIGN	u1t_p = u1t_p + 1l;	
ASSIGN	*u1t_p = (unsigned char)stt_s.b34;	

Fig. 5. Goto-program.

and considers the status of the previous control step as necessary. The command is `goto-analyzer --dependence-graph-vs --structs --arrays --periodic-task`

The CAT exploits the constant and variable sensitivity domains to handle loops and pointers and the dependency abstract interpreter for extracting program dependency. Finally, that outputs the dependency at the instruction-level to Orient-DB.

4.2 Orient-DB

The Orient-DB [8][11] handles the dependency information that comes from a half million lines of code and CPROVER's abstract interpreter (`goto-analyzer`). The sum of the control and data dependencies is approximately relations 445,000 from a half million lines of code. In general, applying a database is reasonable to handle such an enormous amount of information. One feature is that we apply the oriented graph based database "Orient-DB". This is because the code dependency is considered as a directed graph. Each instruction can be considered a "vertex", and each dependency can be considered an "edge". From that perspective, the impact analysis can be implemented as a backward and forward analysis from any slicing criterion.

Figure 6 shows the data structure that is stored in Orient-DB. The vertices represent the instruction, the function, the global variable, and the local variable.

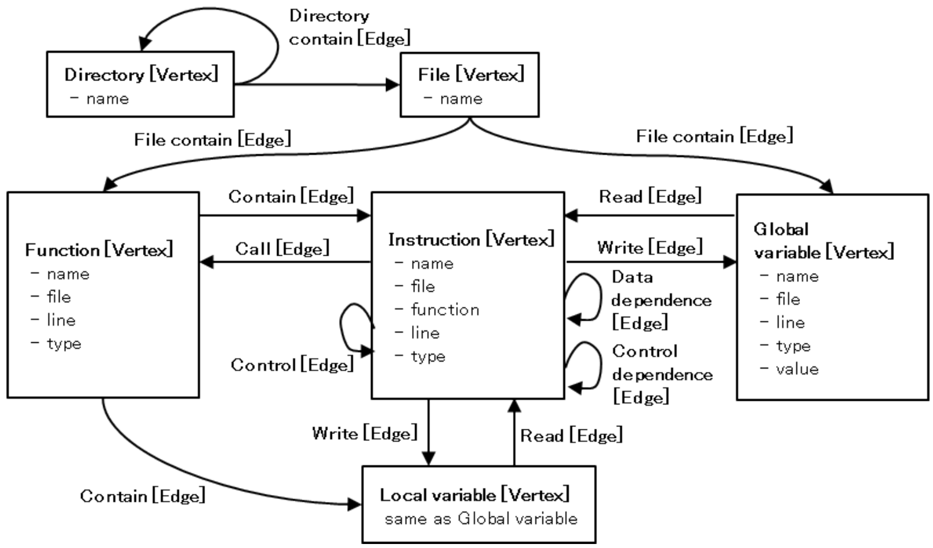


Fig. 6. Orient-DB data architecture.

Those are based on the C-code intermediate format from the goto-program. In addition, the file directory and the file are included to support the directory and file-level merging in the visualization layer. The edges represent the call, the control that expresses the instruction ordering, variable read, and write as in a typical program data dictionary. In addition to that, the data and control dependency that come from the dependency abstract interpreter are registered.

The Orient-DB supports the edge based backward and forward analysis. CAT exploits that for **Backward and Forward Analysis** ((5) in Fig. 4).

4.3 Visualization

The visualization component relates **Visualization** ((6) in Fig. 4). The Orient-DB can extract the vertices that correspond to instructions from the goto-program with any Orient-DB commands. It is easy to imagine that such an instruction-level graph may be difficult to understand. In practice, it is more detail than required to understand the software architecture for most cases.

The designers need to understand the system-level, but they mainly focus on a particular module they are developing. Thus, the graph vertex that relates the module they are developing should be provided in detail; like the module or function-level, other vertices should be abstract like the sub-system or system-level. In that sense, this component is allowed to violate the CPROVER and Orient-DB's data-structure (Fig. 6) and generates the visualized graph so that it is easy to understand. In this layer, vertices can be merged or expanded to and level, like function, file, and folder-level, using a manual command. In accordance with the vertex merging, the edges that include the control, data dependency and the function call are merged as an edge automatically (See Fig. 7). The output

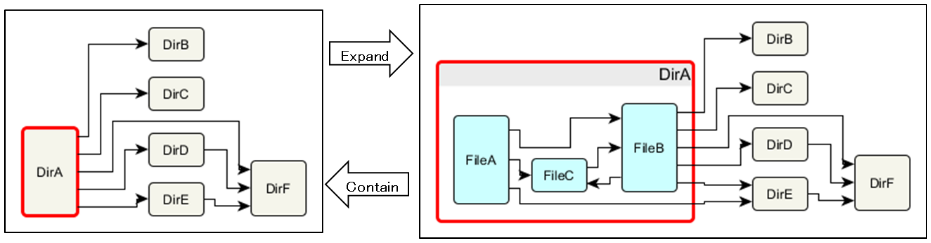


Fig. 7. Example of visualization process.

graph format is GraphMl [12]. yEd Graph Editor [13] is used as a viewer, and the Graph layout is used independently from the CAT to show the result. This component is also implemented in Java.

5 Experiment of CAT with Automotive Unit-System

We evaluate the CAT's unit-system dependency graph generation and the impact analysis with actual code. We choose the engine ECU that is the largest scale in the vehicle system and has a half million of LoC. All experiments were run on a workstation computer with Intel® Xeon® CPU E5-2690, 2.9GHz, 8 cores, 2 processor, and 256GB RAM on OS Ubunutu 16.04.

5.1 Result of Analysis for small examples

This section explains the result of CPROVER `goto-analyzer` in Sec.4.1.

Dependency Analysis The result of dependency analysis `goto-analyzer --dependence-graph-vs` of Program 1 is shown in Fig. 8, which indicates the data dependency has offset of struct member.

The result of dependency analysis of Program 2 is also shown in Fig. 9, which indicates the control, data, and periodic dependency (shown as "later" on edge from L13 to L10 node) are extracted correctly. Above results indicate the requirements those are mentioned in Sec. 2.3 are satisfied. All those dependencies are exported in JSON format and stored to Orient-DB.

Pointer Resolution The first step of pointer resolution using CAT is unwinding the loops. Program 6 shows the result of loop resolving `goto-analyzer --constant` of program 3 in Sec. 2.3 by using the constant abstract interpreter. The `for` loop on L10 in Program 3 is unwound and converted to `if` statements. Program 7 shows the result of pointer resolving `goto-analyzer --variable --structs --arrays` of Program 6. This result shows the abstract interpreter can resolve complex pointer accesses that include loop and array access.

Program 8 also shows the result of function pointer resolving of program 4. Actually because of implementation difficulties, it is solved by using a heuristic

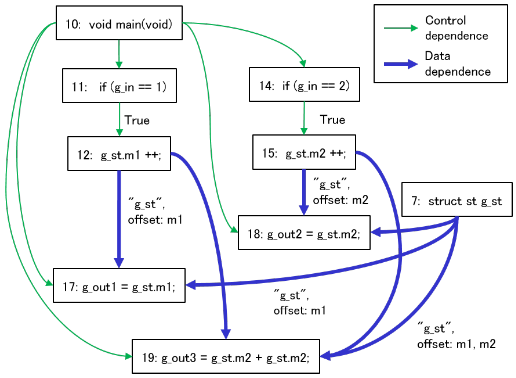


Fig. 8. Dependence result of Program 1

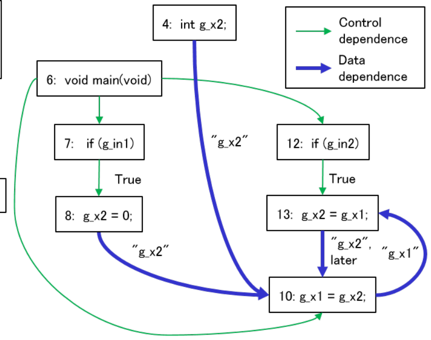


Fig. 9. Dependence result of Program 2

Program 6. Unwound code of Program 3.

```
const signed int cAarray[41]={ 10, 20, 30, 40 };
signed int gArray1[41];
signed int gArray2[41];

void main(){
  const signed int *p0=cAarray;
  signed int *p1=gArray1;
  signed int i=0;
  if(!(i >= 4)){
    *p1 = cAarray[(signed long int)i];
    gArray2[(signed long int)i] = *p0;
    p0 = p0 + 1l;
    p1 = p1 + 1l;
    i = i + 1;
    if(!(i >= 4)){
      *p1 = cAarray[(signed long int)i];
      gArray2[(signed long int)i] = *p0;
      p0 = p0 + 1l;
      p1 = p1 + 1l;
      i = i + 1;
      if(!(i >= 4)){
        *p1 = cAarray[(signed long int)i];
        gArray2[(signed long int)i] = *p0;
        p0 = p0 + 1l;
        p1 = p1 + 1l;
        i = i + 1;
        if(!(i >= 4)){
          *p1 = cAarray[(signed long int)i];
          gArray2[(signed long int)i] = *p0;
          p0 = p0 + 1l;
          p1 = p1 + 1l;
          i = i + 1;
          __CPROVER_assume(!(i < 4));
        }
      }
    }
  }
}
```

method `goto-instrument --remove-function-pointers`. The function pointer access `p->req(len, buf)` on L21 in Program 4 should be function `f1` or `f2`. However, this heuristic method solves as all possible function; `f1`, `f2`, `g1`, or `g2` in over-abstract (See L20-L50 in Program 8.). Potentially the abstract interpreter can reduce the set of possibilities and it is one direction of future development.

Program 7. Pointer resolved code of Program 3.

```
const signed int cAarray[41]={ 10, 20, 30, 40 };
signed int gArray1[41];
signed int gArray2[41];

void main(){
  const signed int *p0=cAarray;
  signed int *p1=gArray1;
  signed int i=0;
  gArray1[01] = 10;
  gArray2[01] = 10;
  p0 = &cAarray[11];
  p1 = &gArray1[11];
  i = 1;
  gArray1[11] = 20;
  gArray2[11] = 20;
  p0 = &cAarray[21];
  p1 = &gArray1[21];
  i = 2;
  gArray1[21] = 30;
  gArray2[21] = 30;
  p0 = &cAarray[31];
  p1 = &gArray1[31];
  i = 3;
  gArray1[31] = 40;
  gArray2[31] = 40;
  p0 = &cAarray[41];
  p1 = &gArray1[41];
  i = 4;
  __CPROVER_assume((_Bool)1);
}
```

5.2 Visualization for Automotive Unit-System

Figure 10 shows the engine unit-system dependency graph, where the red-line shows the extracted result of program slicing. The slicing criteria is an important variable for the engine control software and for the back-forward control and data-dependency analysis. The top segment of this figure shows the feature layer. The middle segment shows the module graph. The bottom segment shows the function and global variable graph. This figure shows the unit-system level, the feature level, and the module level hierarchically and with the designer preferred abstraction. The result shows that the program slicing gives the information the designer should focus on.

The time and memory consumption was evaluated while generating Fig. 10. First, the CAT compiling CPROVER compiler ((1) in Fig. 4) takes about 24 minutes. The abstract interpreters, the constant abstract interpretation ((2) in Fig. 4), the variable abstract interpreter ((3) in Fig. 4), and Dependency Abstract Interpreter ((4) in Fig. 4), which are for the dependency analysis, take about 7 hours and consumes a maximum of 198 GB memory. Forward and backward analysis (((5) in Fig. 4)) and Visualization ((6) in Fig. 4) take up to a few minutes.

In total, the CAT takes about 8 hours while consuming up to 198 GB RAM. It is done fully automatically and means the CAT can reduce work-hours dramatically compare with manual or semi-manual manner. Furthermore, it is practically impossible to extract such exhaustive dependency information manually.

Program 8. Pointer resolved code of program 4..

```
struct st;
signed int f1(char, char *);
signed int f2(char, char *);
void func(signed int id, signed int len, char *buf);
signed int g1(char, void *);
signed int g2(char, void *);

struct st{
  signed int (*req)(char, char *);
};

const struct st fptbl1[21];
const struct st fptbl1[21]={ { .req=f1 }, { .req=f2 } };
signed int (* const fptbl2[21])(char, void *);
signed int (* const fptbl2[21])(char, void *)={ g1, g2 };

void func(signed int id, signed int len, char *buf){
  const struct st *p=&fptbl1[(signed long int)id];
  p->req;
  if(!(p->req == f2))
  {
    if(p->req == (signed int (*)(char, char *))g1)
      goto __CPROVER_DUMP_L2;

    if(p->req == f1)
      goto __CPROVER_DUMP_L3;

    if(p->req == (signed int (*)(char, char *))g2)
      goto __CPROVER_DUMP_L4;
  }

  f2((char)len, buf);
  goto __CPROVER_DUMP_L5;

__CPROVER_DUMP_L2:
  ;
  g1((char)len, (void *)buf);
  goto __CPROVER_DUMP_L5;

__CPROVER_DUMP_L3:
  ;
  f1((char)len, buf);
  goto __CPROVER_DUMP_L5;

__CPROVER_DUMP_L4:
  ;
  g2((char)len, (void *)buf);

__CPROVER_DUMP_L5:
  ;
}
```

5.3 Examination of Preciseness and Scalability

In this section, we discuss the exhaustiveness of the abstract interpreter and the Orient-DB. Table 3 shows the scalability of the abstract interpretation. It shows the calculation time and memory consumption from several levels: task, module, and function. Every entry is the largest function in each levels. The related preciseness combinations are shown in Table 1. Each LoC refers to the scale of the code. The LoC is estimated from the goto-program, which completely resolves the loop and the context. Figure 11 shows the memory consumption Fig. 12 shows the trends of time and for each abstract interpreter.

This result illustrates the possibility that the abstract interpreter can coordinate the scalability and the preciseness according to the designers PC spec. One of contributions of CAT is the decrease in work-hours for pointer-resolving,

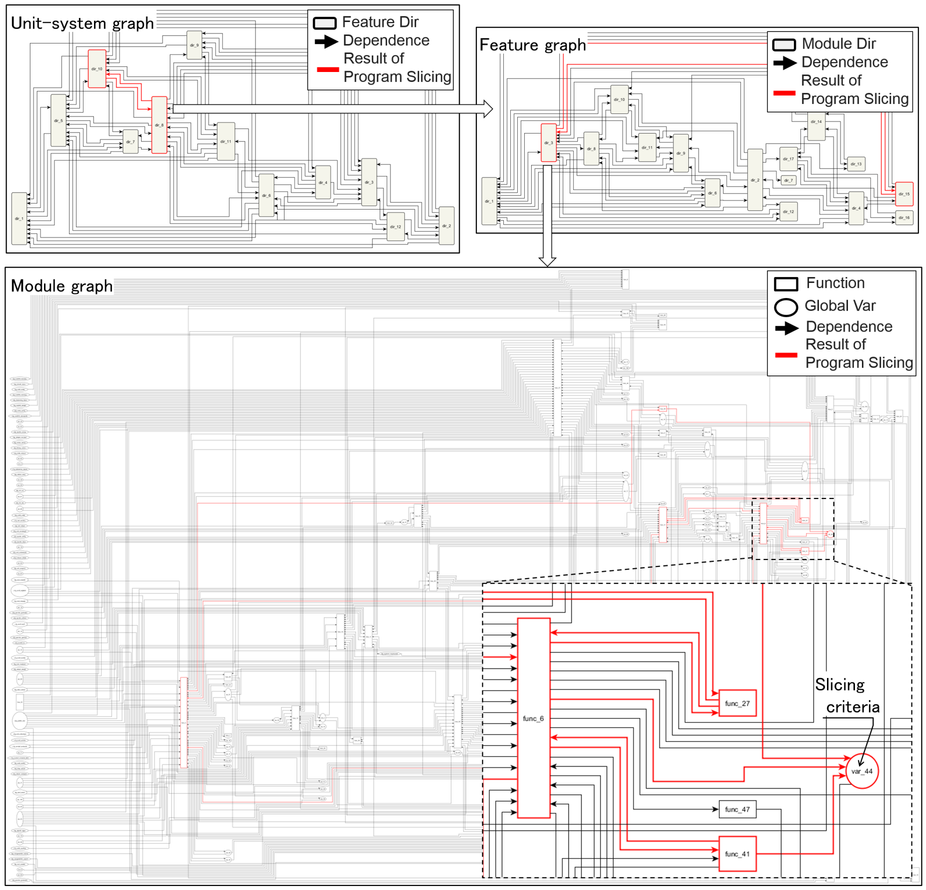


Fig. 10. Engine unit-system dependence graph.

which is expected to take about 125 hours to resolve five hundred pointers manually (Sec. 2.3). As row "Unit #1-4" and column "Variable Time" shows, the variable abstract interpreter resolves the pointers from the largest unit entry in around 50 minutes. Actually we need to solve several unit entries, even though it can resolve in about 2 hours.

The program slicing is implemented using Orient-DB's backward and forward analysis on the oriented graph. There are 200 thousand instructions treated as vertices, 410 thousand control/data dependencies, which are treated as edges. We have not compared any data bases; however table 2 shows Orient-DB can extract 5,949 instructions from 8 slicing criteria on a half million items related to dependency in 1,349 msec. The search speed is extremely fast and well satisfied our use-case.

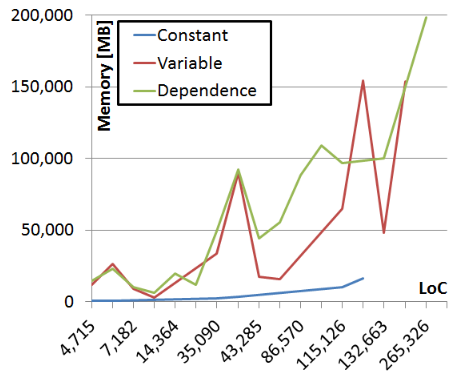


Fig. 11. Memory consumption.

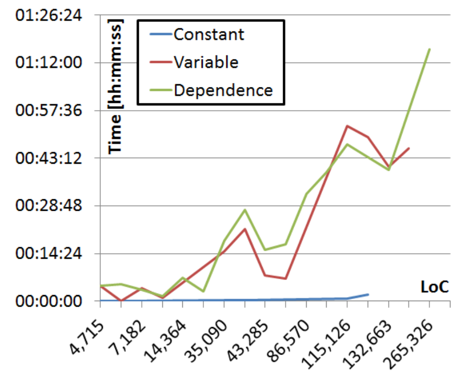


Fig. 12. Time consumption.

Table 1. Combination of preciseness options.

Precisness	Flow	Context	Loop	Recurrent
#1	✓			
#2	✓	✓		
#3	✓		✓	
#4	✓	✓	✓	
#5	✓		✓	✓
#6	✓	✓	✓	✓

Table 2. Evaluation of Orient-DB.

# Criterion	# Extracted instructions	Time [ms]
1	146	68
2	419	146
3	536	188
42	3,562	1,065
88	5,949	1,349

The total num. of instr. is 200k.

Table 3. Evaluation of abstract interpretation.

Entry	Pre.	LoC	Constant		Variable		Dependence	
			Memory [MB]	Time	Memory	Time	Memory	Time
Module	#1	4,715	540	00:00:04	12,015	00:04:45	14,395	00:04:42
	#2	5,766	558	00:00:04	26,460	0:0:5:45	22,849	00:05:02
	#3	7,182			8,843	00:03:49	10,137	00:03:19
	#4	8,779			3,158	00:01:07	6,280	00:01:30
	#5	14,364					19,740	00:07:10
	#6	17,558					11,975	00:02:50
Feature	#1	35,090	2,528	00:00:13	33,756	00:15:02	49,033	00:18:12
	#2	34,874	3,222	00:00:23	89,819	00:21:51	92,351	00:27:39
	#3	43,285			17,664	00:07:41	44,260	00:15:34
	#4	50,072			15,770	00:06:46	55,348	00:17:10
	#5	86,570					88,239	00:32:28
	#6	100,144					109,197	00:38:56
Unit	#1	115,126	10,200	00:00:50	64,753	00:53:01	96,699	00:47:14
	#2	123,881	16,390	00:02:06	154,118	00:49:36	out of memory	
	#3	132,663			48,008	00:40:41	99,864	00:39:33
	#4	155,178			153,872	00:46:15	out of memory	
	#5	265,326					198,149	01:16:06
	#6	310,356					out of memory	

5.4 Discussion of Preciseness and Scalability

As demonstrated above, CAT can provide the unit-system dependency graph (See Fig. 10). In this section, we discuss the CAT's components; CPROVER, Orient-DB, and Visualization.

CPROVER mainly provides the abstract interpreter, which is one of two key technical items. The abstract interpreter solves the pointer and the dependency at the instruction level. Table 3 shows the possibility of coordinating the scalability and the preciseness; however, the scalability still remains an issue. The abstract interpreter consumes up to 198 GB of memory, furthermore, Unit #1, #4, and #6 are out of memory. Actually, Unit #5 satisfies our visualization use-case (the context sensitivity or more precise analysis is not needed.). In general, that is too heavy to perform on a standard desktop PC, but the performance requirement can be overcome by sharing the Orient-DB repository via a network as the host. In this case, the computing demand on the local PC is not as high.

From this experience, not only the large program scale (half million LoC) but also the many (several thousands of) global variable impacts the scalability. There are two main reasons for this. First, the domain information for each global variable cannot be released because they are "global" variables. Second, every global variable domain (status) needs to be stored for each instruction. This means the memory consumption is a multiplication of the number of global variables and LoC, approximately. The embedded controller cannot avoid using the global variable, and we typically cannot expect to decrease the LoC. The only way is to lessen the domain scale and update the domain objects.

The essential advantages of abstract interpretation are the soundness and the ability to trade off the preciseness with the computation time. The ideal usage is applying the abstract interpreter in a hierarchical fashion; meaning, in the early phase, use a less precise (scalable) abstract interpreter to simplify (erase dead code, simplify pointers), then in the later phase, gradually apply a precise (less scalable) abstract interpreter to the simplified code. The CAT exploits the abstract interpreter in this way; however, our design of data structures for the Orient-DB (Fig. 6) deals with the most precise instruction-level of the information and does not consider intermediate information like unwound-bounds and pointer simplifying. More sophisticated data-structures that can deal with the history of the result from the abstract interpreter are needed to better exploit the abstract interpreter.

In the visualization component, the on-demand access that is supported by the Orient-DB realizes a user preferred level for the graph (Fig. 7) to provide the enormous dependency information from a half million lines of code. On the other hand, the graph placement is a further issue related to the large size of the graph. The yEd Graph Editor is used in this paper separately from CAT and the default placement setting is used, but the preference for the placement depends on the domain. We need to consider those settings for each domain to deploy CAT. The yEd allows user specific placement settings. We expect it can implement this by using the yEd API.

5.5 Future Work

Authors think the CAT tool achieved a trial level, even though still there remain improvement items. The biggest advantage of the CAT is that is capable to extracting the exhausting dependence analysis which includes pointer analysis with just one night. We have already presented a demo to designers. They are also interested in the capabilities of scalability and, the result of program slicing; even though it is the function level graph, the slicer extracts well because of the statement level of dependence analysis is done in behind. (See bottom of Fig. 10, the slicer does not extract all of input edges at `func_6`.)

We are planning trial with 3 domains; Vehicle Control, Engine and Fuel Cell domain. The vehicle control domain is rapidly increasing the work-hours due to applying Automated Driving Technology. The engine still remains the largest scale of controller in automotive. The fuel cell system is also complex system which involves FC stack, Battery, and Electric motor. We expect the around 8,000 hours' reduction of work-hours per an ECU development when the CAT is deployed.

6 Conclusion

In this paper, we focus on the enhancement of control software development processes in the early development phases. The technical difficulty relates to the management of up to half a million lines of code per ECU. We applied an advanced static analysis method, abstract interpretation, to address function pointers and variable pointers and to extract an instruction-level of dependency. We systematize this process in the CAT tool, which uses CPROVER and Orient-DB. The CAT tool can handle a half million lines of code, resolve 500 pointers, and extract a half million dependencies within 8 hours. CAT provides system graphs to understand software architecture on demand. CAT is a flexible and sophisticated tool for reviewing code in early development phases.

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