AJcFgraph - AspectJ Control Flow Graph Builder for Aspect-Oriented Software

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Abstract—The ever-growing usage of aspect-oriented development methodology in the field of software engineering requires tool support for both research environments and industry. So far, tool support for many activities in aspect-oriented software development has been proposed, to automate and facilitate their development. For instance, the AJcTS provides a transformation system to support aspect-oriented development and refactoring. In particular, it is well established that the abstract interpretation of programs, in any paradigm, pursued in static analysis is best served by a high-level programs representation, such as Control Flow Graph (CFG). This is why such analysis can more easily locate common programmatic idioms for which helpful transformation are already known as well as, association between the input program and intermediate representation can be more closely maintained. However, although the current researches define the good concepts and foundations, to some extent, for control flow analysis of aspect-oriented programs but they do not provide a concrete tool that can solely construct the CFG of these programs. Furthermore, most of these works focus on addressing the other issues regarding Aspect-Oriented Software Development (AOSD) such as testing or data flow analysis rather than CFG itself. Therefore, this study is dedicated to build an aspect-oriented control flow graph construction tool called AJcFgraph Builder. The given tool can be applied in many software engineering tasks in the context of AOSD such as, software testing, software metrics, and so forth.

Keywords—Aspect-Oriented Software Development, AspectJ, Control Flow Graph, Data Flow Analysis

I. INTRODUCTION

Aspect-Oriented Programming (AOP) [1] is a relatively new paradigm that can be used to achieve a higher level of modularization, by means of separation of core concerns from crosscutting concerns, in source code than traditional non-aspect-oriented approaches. However, AspectJ [2] is a seamless aspect-oriented extension to Java, which is the most widely used aspect-oriented programming language. AspectJ adds some new concepts and associated constructs are called join points, pointcut, advice, inter-type declaration, and aspects into standard Java programming language.

Moreover, support for program analysis is crucial in modern programming languages. Especially, a control flow graph is one of the most basic information of a program to analyze various properties of a program, which in turn would be useful in many ways. However, due to the specific features and language constructs such as join points, advice, introduction, and aspects in Aspect-Oriented (AO) languages, the control-flow analysis for AO programs is more difficult and challenging than that for object-oriented programs, so that the current techniques in procedural or object-oriented paradigm are not able to address these features. Therefore, a good algorithm or technique to derive the control-flow graph for AO programs is valuable and important.

Furthermore, once control flow graphs are obtained they can be applied in many software engineering tasks in the context of AOSD such as software testing, software measurement or metrics, software maintenance, and concern interactions. For instance, it stands to reason that the behavior of an aspect-oriented system is the woven behavior of the aspects and the core; but this woven behavior may reveal conflicts in the goals of the system concerns, core or crosscutting, where such conflicts are called concern interactions (e.g. advice overlaps, where multiple advice applies to the same join point, which can be viewed as potential source of interaction) and may cause ripple effects on the overall AO system, therefore a CFG of the given system would be helpful as map to detect or reveal an easier identification of those point of impacts. Besides, imagine one wants to obtain the CFG of a given AO system manually, therefore a vast of energy probably with less accuracy will be accounted to do so.

On the other hand, although many CFG constructing approaches have been proposed for procedural and object-oriented programming, but there are only a few works in literatures including [3]–[7] are involved with generation of control flow graphs for aspect-oriented programs. These works even though define the concepts and foundations, to some extent, for control flow analysis of aspect-oriented programs but they do not provide a concrete tool that can solely construct the CFG of these programs. Furthermore, most of these works focus on addressing the other issues with respect to these programs such as testing or data flow analysis rather than CFG itself, in which they give a little attention to the detailed information of CFG construction process or its tool support. Therefore, an efficient technique and tool that are appropriate for constructing CFG of aspect-oriented programs are needed. This work presents an algorithm for constructing the control flow graph of AOPs and its tool support. The proposed approach and its given tool can be used to provide
useful support to solve the aforementioned issues and other problems for many software engineering tasks in the case of aspect-oriented programming.

The rest of the paper is organized as follows: Section II discusses related work; Section III presents the tool architecture; Section IV gives the explanation of the code compilation unit; Section V describes the data structures used in the given tool; Section VI presents the proposed approach for analyzing the CFG of ascepts as well as, the algorithm that takes care of constructing the control flow graph of aspect-oriented programs named BuildAOCFG; Section VII discusses the feasibility and applicability of the builder; Section VIII reports the conclusion and future work on this work.

II. RELATED WORK

Several and different forms of control flow graphs have been proposed along the years for procedural or object-oriented paradigm [8]–[11] to address the change in advance of programming technologies. However, as the adoption of AOP in software development is gaining ground [3], some code representation forms for AOP have been proposed in recent years researches based on CFG, which in turn provide information for analyzing AspectJ or similar AOP language programs. Moreover, most of these works are focused on data flow graphs and testing criteria for aspect-oriented programming including [5],[7],[12], of course generation of a dataflow graph usually requires a control flow graph in advance but they do not provide the detailed information of CFG constructing process especially its tool support.

A preliminary contribution is from J.Zhao. J.Zhao in [4] proposes a technique to construct control flow representations for aspect-oriented programs. Although his work defines good foundations, our work is inspired by it to some extent, for constructing CFG of aspect-oriented programs but it does not provide a tool which is capable of putting those theories and definitions into practice. In addition, the proposed technique cannot handle the around advice in the process of constructing control flow graphs, where this issue is taken into account in our work.

O.A.L.Lemos, A. M.R. Vincenzi, J.C. Maldonado and P. C. Masiero in [5] propose the derivation of a control and data flow model for aspect-oriented programs based upon the static analysis of the object code (the Java bytecode) than source code level which resulted from the compilation process. Using this model, called aspect-oriented def-use graph (AODU), traditional and also aspect-based testing criteria were defined. Furthermore, a prototype tool called JaBUTI/AJ was proposed to support proposed criteria and given model. One of the issue associated with this approach, since it works on bytecode than source code, is difficulty in building and preserving a map that relates the data flow effects of each entity in bytecode back to its corresponding entity in source code. Furthermore, the obtained map is also subject to change form one compiler to another since different compiler can produce totally dissimilar mapping. Therefore, such issues can be addressed though a source code level approach like [6].

More recently, G. Xu and A. Rountev in [6] propose a source-code-level framework called AJANA (AspectJ ANAlysis) for interprocedural dataflow analysis of AspectJ programs. The results associated with the evaluation of the framework shows that the given approach is superior to an approach based on the woven bytecode like in [5] which in turn enables analyses to be both faster and more precise as well as, being a promising candidate for systematic foundations of dataflow analysis in AspectJ programs. The proposed framework was implemented as extension to the abc AspectJ compiler.

Besides, AJDT (AspectJ Development Tools) [13] on Eclipse provides some information on aspect-oriented programs. With this, although it is possible to construct a simple CFG builder for AspectJ programs but it is not a straightforward process and still needs codification and integration of some other tools such as XRef, Visualizer, or Build path configuration in order to obtain those required information for constructing CFG of AspectJ programs.

Although these approaches provide good foundation for control flow analysis of AOPs and may able to construct the CFG of aspect-oriented programs as a built-in process, but they do not present a concrete tool that can do this, which consequently make them to be not applied directly to construct a complete CFG of aspects due to either remaining in theory than practical or aforementioned issues associated with them. The work presented in this paper is a source-code-level approach which can handle the problems of constructing the CFG of AspectJ software that are unique to aspect-oriented programs, by proposing a tool call AJcFgraph, with a high-level program analysis and program understanding.

III. TOOL ARCHITECTURE

The tool, AJcFgraph Builder, is developed to automate the construction of the AOCFG (section VI). The following, Fig. 1, outlines the high-level architecture of a system for constructing and managing the AOCFG representations in the given tool. In other words, it illustrates the conceptual view of AJcFgraph Builder’s process flow and interaction among its components.

![AJcFgraph Builder architecture model](image)

The given tool is object-orientedly designed and implemented in Java programming language. The main components of the tool, as shown in Fig. 1, are as follows:
• Parser, which is used to parse AOP code written in AspectJ on the base of modification of abc (AspectBench Compiler).
• Algorithm, which builds the MCFG, pAOCFG, and AOFCG based on AST of each compilation unit obtained in parsing process.
• Graph visualizer, which is used to portrait the obtained AOFCG graph on the screen.

In the following sections each of above component and their basic properties of implementation is described in more detail. Where each is studied in terms of input used, mechanism, library, or framework applied, and output that it produces in the flow of process.

IV. CODE COMPILATION UNIT

Generally, this unit is used to analyze the input program to get control flow information such as the predecessors and successors of each statement, caller/called information and finally identification of each module in aspects or classes, which are necessary for constructing the control flow graphs.

The compilation unit has two main components: the source code parser and code model maker. The unit uses the parser to parse input source code written in AspectJ and produces a parse tree, then uses the code model maker to build the code model for the input source from the parse tree produced by parser. Simply, it transforms the given parse tree into an Abstract Syntax Tree (AST).

A. Source Code Parser

The parsing itself is a process with two levels of grammar, as shown in Fig. 2, which are lexical and syntactic. In other words, a context-free grammar [17] is used to define the syntax of AspectJ language by using two sets of rules: lexical rules and syntactic rules.

Fig. 2 Process of parsing AspectJ source code

1) Lexical Structure: The lexical analysis of AspectJ is complicated by the fact that there are really three different languages being parsed: (1) normal Java code, (2) aspect declarations, and (3) pointcut definitions [17]. Therefore, to this end, each of these three sub-languages should have its own lexical structure and implementation, as addressed in AjFgraph Builder.

2) Syntactic Structure: Once the grammars and tokens (using lexer) are determined, the implementation of the syntactic part of the given parser would be straightforward. To this end, the PPG [18] framework is used, in this work, to handle the LALR (1) grammars of AspectJ language as well as, tokens produced by lexical component. Besides, PPG allows changes to an existing grammar to be entered in separate file, overriding, inheriting and extending production from the base grammar. This result in modular extensions, which can easily be maintained should the base grammar change.

B. Code Model Maker

The given component simply traverses the parse tree and constructs code model objects from the parse tree, which is used as program’s sole intermediate representation that seeds the algorithm. Then it performs all the static checks required by a number of passes which rewrite the tree. Moreover, semantic checks are implemented by considering appropriate methods on the relevant AST node, where every AST node implements a typeCheck (TypeChecker) method. The type checker is run after all variable references are resolved; all checks that do not require further data structures are typically put in the typeCheck method.

The Fig. 3 illustrates the overall view of code mode maker, where it gets the parse tree as input and produces the AspectJ model in the form of AST.

Fig. 3 Code mode maker macro view

The code model maker is actually a set of classes that are capable of simulating the AST of given parser specification

1 The given compiler is based on Polyglot extensible compiler framework [14] and the Soot byte code analysis and transformation framework [15], which forms the frontend and backend of abc respectively.
(based on parse tree) [19]. The AST itself only contains AspectJ and Java constructs where the specific-language details are removed. Furthermore, the elements of the tree are implemented as instances of classes. Instance variables of the AST classes are used to represent the children of the node. Instance variables of leaf nodes are used to hold information about the node’s value, e.g. literal values, references into a symbol table, etc. All of the AST node classes are directly or indirectly derived from an abstract base class. A common super/base class of nodes can be as follows:

```java
public abstract class Node implements Switchable, Cloneable {
    public abstract Object clone();
    void parent() {...}
    void parent(Node parent) {...}
    abstract void removeChild(Node child);
    abstract void replaceChild(Node oldchild, Node newchild);
    public void replaceBy(Node node) {...}
    protected String toString(List list){...}
    protected String toString(Node node){...}
    protected List cloneList(List list){...}
    protected String to_string(Node node){...}
    protected String to_string(List list){...}
}
```

In this tool two alternatives in designing AST nodes are used, “smart” objects and “dumb” objects. If there is only one client for the AST, the smart object approach is used. Where, the nodes of the AST provide a method for performing the work the client requires. If there are multiple clients, then dumb objects should be used. With dumb objects, there are few or no methods implemented by the AST nodes. Furthermore, to perform work with the ASTs, the VISITOR pattern is used. The Polyglot’s visitor-based architecture makes implementing much easier. In this case, two new passes are added. The first stores all global pointcuts in a static variable, and the second applies that pointcut to the relevant code. For reason of code brevity, in given tool implementation, these two passes are implemented by the same class, named GlobalAspect; it uses a member variable called pass to distinguish which of the two functions it is performing. On the other hand, to instantiate the VISITOR pattern for the implement AST pattern, a visit method is defined in each AST. The visit method has a parameter for the Visitor object. The Visitor object might do type-checking, code-generation, etc as well (note, Visitor pattern is used to implement traversals when using dumb objects). Therefore, class definitions for the abstract syntax tree are built from the parser specification. The following is an example for the AST class discussed in the above:

```java
abstract class AST {

} public class Variable extends AST { public Identifier id;
public Variable(Identifier id) {
    this.id = id;
} }
```

## V. DATA STRUCTURE

This section briefly describes the data structure used in AJcFgraph Builder. The data structures are what are common across all analysis modules in the given tool. One of the key techniques devised in our tool, in order to support AOP features and ease of the analysis development, is the presented data structure. What the data structures represent is explained in the following sub-sections.

### A. Graphs, Nodes, Edges

Graphs represent program elements and the relationship between these elements. The program elements are represented as nodes, and the relationships are represented by edges. Different nodes can represent the various program elements in a Java application, and the different edges are used to represent the different relationships between the program elements.

All edges are directed and therefore have a source and destination. Adding new relationships involves adding a new class that extends the abstract Edge class. All edges can have their own properties. This is especially important for the visual representation of the graphs that can be generated. For example, in control flow graph, a call edge is a dashed arrow or an intra-module control flow edge is only arrow.

Nodes are more complicated. A node holds an object which represents a program element. This object can either be a Soot object [15], or a NodeElement object. Soot objects are only used by GraphMaker (section VI.D) while constructing a graph, so once a graph is made, all reference to Soot objects are replaced with references to NodeElement objects. This ensures serializability and also that there are no references to Soot from anywhere in AJcFgraph Builder once a graph is made. The NodeElement is an abstract class which contains two abstract methods, getSignature and setSignature. Each concrete class must implement these methods. This signature is the actual representation of some program element. The format of these signatures is the same as those used in Soot [16]. The reason the signatures are not stored directly into the nodes is because these signatures represent the most elementary program element in Java, whereas there are some NodeElements that are associated with more than one Node. For example, a class can be abstract, or it can be an interface, or it can be a regular class. Each of these is represented by a different node; however, all these different nodes contain an object of type Class, which is a NodeElement, and their signature formats will be the same.

### B. Groups

Groups represent an ordered set of nodes from a graph. The order is based on the order in which nodes are added to the group. There are two types of Group, JGroups and Vectored-Statistics.

There are two main differences between JGroups and
VectoredStatistics. The first is that JGroups can only contain nodes, whereas VectoredStatistics can contain both nodes and JGroups. The second is that JGroups are supposed to represent sets of nodes generated by a graph traversal performed by the GraphTraverser (section VI.E) component. VectoredStatistics represents sets generated by the GraphAnalyzer (section VI.F) component.

C. Marks

Marks represent objects that can be attached to Node, Edge, or Graph. Mark can hold any type of object. Marks are used to attach information to other elements. This information can be weight, distance, a string representing color, or any other attribute that the other elements may require.

VI. THE PROPOSED APPROACH AND BUILD AOCFG ALGORITHM

The control flow graph used in procedural systems, non-AOP languages, has been extended to be applicable for object-oriented system as ECFG [20]. ECFG is a collection of CFGs in a layered manner where nodes refer to module, e.g. methods, rather than statements (in contrast with procedural).

Our approach, in the case of aspect-oriented, shares the same viewpoint with OO approach in the sense that a control flow graph for AOP is also a collection of CFGs in a hierarchical manner but further since an AO program (in contrast with OO program that is only base code e.g. classes) is divided into two parts: base code which normally includes classes, interfaces, and standard Java features or constructs and aspect code which put into practice the crosscutting concerns in the program by using aspect, advice, etc; the interaction between these two parts as well as unique features of AOP must be considered. To this end, three layers or hierarchies towards coming up with the final control flow graph of AOP are defined; where each layer denotes a special named CFG that captures some part of an AO code as well as, utilizing the lower layers as part of its construction process.

The Fig. 4 depicts the macro view of three layers and their name with respect to proposed approach, where lower layers are used in the upper layers in order to form a hierarchical structure of CFGs, which results in the final control flow graph called Aspect-Oriented Control Flow Graph (AOCFG).

Besides, a modified version of an AspectJ program taken from [21] is used as small AOP named ShadowTraker, throughout this section in order to introduce example with respect to approach. Fig. 5 gives the AspectJ code, which consists of two classes (Point and Shadow) and one aspect (PointShadowProtocol) that associates shadow points with every point object. For brevity, some implementation details such as import packages are omitted from the figure.

```
1 public class Point {
2     protected int x, y;
3     public Point(int _x, int _y) {
4         x = _x;
5         y = _y;
6     }
7     public int getX() {
8         return x;
9     }
10    public int getY() {
11         return y;
12     }
13     public void setX(int _x) {
14         x = _x;
15     }
16     public void setY(int _y) {
17         y = _y;
18     }
19     public void printPositionP() {
20         System.out.println("Point at( "+x+" ,"+y+")");
21     }
22     public static void main(String[]  args) {
23         Point p = new Point(1,1);
24         p.setX(2);
25         p.setY(2);
26     }
27    }
28
class Shadow {
29     public static final int offset = 10;
30     public int x, y;
31     Shadow(int x, int y) {
32         this.x = x;
33         this.y = y;
34     }
35     public void printPositionS() {
36         System.out.println("Shadow at ("+x+","+y+")");
37     }
38     private int shadowCount = 0;
39     public static int getShadowCount() {
40         return PointShadowProtocol.aspectOf().shadowCount;
41     }
42     public static void associate(Point  p, Shadow s) {
43         p.shadow = s;
44     }
45     public static Shadow getShadow(Point  p) {
46         return p.shadow;
47     }
48     private Shadow Point.shadow;
49     // its own methods
50     public void printPositionS() {
51         System.out.println("Shadow at ("+x+","+y+")");
52     }
53     public static final int offset = 10;
54     public int x, y;
55     Shadow(int x, int y) {
56         this.x = x;
57         this.y = y;
58     }
59     Shadow() {
60         // constructor
61     }
62 }
```
around advice, in the MCFG two nodes, 
point is considered as 
by the around advice (in implementing of the graph for 
considered just before and after the given join point affected 
in the code that contains a call to a method or creating an 
MCFG of a module.

node-after ( 

node-before ( 

around advice for a given join point, our approach 
degraded towards an advice. Note that, in order to handle 
join points in the code where the flow of control can be 
differentiates join point node-before ( 

and method) within an aspect. Given as an aspect consists of 
n modules such that MCFGk = (s1, e1, V1, E1) for k=1,2,....n are 
the control flow graphs of n modules . The partial Aspect-
Oriented Control Flow Graph is defined as a directed graph 
that is a collection of MCFGk ( k =1...n) and edges linking 
them to make up the pAOCFG of the considered system. A 
quadruple: pAOCFGm= (s#, e#, Vm, Em) is used to denote the 
AOCFG, where s# is the aspect start node (or entry node) of 
as and e# is the exit node of the given aspect; similar to 
MCFG these nodes are unique and have in-degree and out-
degree of zero respectively. Vm is constructed by the set of all 
nodes in n modules which form the given aspect as well as, the 
pointcut nodes, which is

\[
V_{as} = \bigcup_{k=1}^{n} V_k \cup V_{ptc}.
\]  

(2) 

Pointcut nodes (V_{ptc} ), representing a set of 
pointcuts in the aspect as. It means each pointcut is represented by a pointcut 
node, ptc, that is used to denote the entry to the given pointcut as well. Lastly, E_{as} is the set of all edges in n modules forming 
as aspect in addition some new types of edges that capture the 
interaction among the modules inside the aspect as, which is

\[
E_{as} = \bigcup_{k=1}^{n} E_k \cup E_{as} \cup E_{ca} \cup E_{pc}.
\]  

(3) 

The E_{as} is the set of aspect-membership edges, which 
denotes the membership relationships between aspect as and 
its components. The E_{ca} is a set of call and return edges. 
These edges represent the caller/called relationships (or control flow) between two modules in as. The E_{pc} represents a set of pointcut edges, which are used to link the ptc nodes to the start node of corresponding advice modules in as to 
represent the relationship, or control flow, between them.

• AOCFG: The third layer is the last hierarchy of the 
constructing process that results in the complete CFG of AOP, 
which is called Aspect-Oriented Control Flow Graph. The 
only difference between this and the pAOCFG is in 
consideration of the interaction between aspects with classes. 
Generally, in AspectJ, an aspect can interact with a class in 
several ways, i.e., by object creation, method call, and advice 
weaving [4]. Therefore, the aspect-oriented control flow graph of 
an AOP should be able to represent these interactions
between aspects and classes as well. Given AO an aspect-oriented program (like that one in Fig. 5) with \( r \) modules in base code or classes (that are affected by aspects) and \( t \) aspects so that \( MCFG_k = (S_k, E_k, V_k, E_k) \) for \( k=1,2,\ldots,r \) are the control flow graphs of \( r \) modules and likewise, \( pAOCFG_p = (S^p, E^p, V^p, E^p) \) for \( p=1,2,\ldots,t \) are the control flow graphs of \( t \) aspects within \( AO \). Therefore, the Aspect-Oriented Control Flow Graph is defined as a directed graph that is a collection of \( MCFG_k\)'s and \( pAOCFG_p\)'s, as well as edges linking them to make up the AOCFG of the whole AO system. On the other hand, since \( pAOCFG \)s are constructed by a set of MCFGs within themselves, therefore it can be viewed that the AOCFG\(_{AO}\) is a collection of all MCFGs no matter from base code or aspect code, where each represents a method (a method of a class, aspect, or main () method), a piece of advice, or an inter-type member. A quadruple: \( AOCFG_{AO} = (S^AO, E^AO, V^AO, E^AO) \) is used to represent the given graph, where \( S^AO \) denotes the start node or the point from which the execution of the given program is started and \( E^AO \) that represents the exit node of the aspect-oriented program, in which the execution of \( AO \) will be terminated; similar to MCFG and \( pAOCFG \) these nodes are unique and have in-degree and out-degree of zero respectively. Roughly speaking, the \( S^AO \) is the same with the start node of the MCFG of main() method in base code, because in AOCFG (in contrast with MCFG or \( pAOCFG \)), the dynamic or running view of whole aspect-oriented program is traced. \( V^AO \) is a set of nodes in \( AO \) that is defined as

\[
V^AO = \bigcup_{k=1}^{r} V_k \bigcup_{p=1}^{t} V^p. 
\]  

Where, the first element is the set of all nodes in \( r \) modules in \( AO \) aspect-oriented program; each represents a call node, statement node, or joint point shadow node. Likewise, the second element is the set of all nodes in \( t \) aspects where each represents a pointcut node, call node, or statement node of modules in aspects. Therefore, in the case of AOCFG, there is no new or additional type of node that is going to be added; whereas it only synthesizes the nodes obtained from the first and second layers, that is

\[
E^AO = \bigcup_{k=1}^{r} E_k \bigcup_{p=1}^{t} E^p \bigcup E_{ca} \bigcup E^AO. 
\]  

The first two elements denote the set of all edges in the corresponding \( r \) modules in \( AO \) aspect-oriented program; each represents a call edge, statement edge, or joint point shadow edge. Meanwhile, the second element is the set of all edges in \( t \) aspects where each represents a pointcut edge, call edge, or statement edge of modules in aspects. Therefore, in the case of AOCFG, there is no new or additional type of edge that is going to be added; whereas it only synthesizes the edges obtained from the first and second layers, that is

\[
E^AO = \bigcup_{k=1}^{r} E_k \bigcup_{p=1}^{t} E^p \bigcup E_{ca} \bigcup E^AO. 
\]  

The first two elements denote the set of all edges in the corresponding \( r \) modules and \( t \) aspects within \( AO \) aspect-oriented program (already obtained from the first and second layers). The \( E_{ca} \) captures the set of the inter-module control flow or call/return edges in interaction of aspects with classes while there is call or object creation. More specifically, in the case of method calls, a call may occur between two modules \( m_1 \) and \( m_2 \) either in aspect or base code. In this case, an inter-module control flow edge is used to link the call node of \( m_1 \)'s MCFG to the start node, \( S_2 \), of \( m_2 \)'s MCFG and in return an inter-module control flow edge from the exit node, \( e_3 \), of \( m_2 \)'s MCFG towards the immediate statement of call node in \( m_1 \) is drawn as well. Besides, in the sense of object creation, a module \( m \) is capable of creating an object of a given class \( C \) either in an aspect or a class. The creation process can be done via class type declaration or by using an operator such as new. In this case, by definition, behind the scene an implicit call will be done from module \( m \) (at the place of object creation) to class \( C \)'s constructor. Therefore, to take into account this implicit constructor call and represent it in AOCFG, an inter-module control flow edge is also used to link the call node of module \( m \) to the start node, \( s \), of the MCFG of \( C \)'s constructor as well as, one edge for returning the flow of control from the \( C \)'s constructor to the module \( m \) is drawn as well. Lastly, \( E_{w}^{AO} \) denotes the set of aspect-weaving edges that captures the advice weaving process in the AO aspect-oriented program. Generally, as mentioned earlier, in AOP new behaviors or functionalities defined by advice are woven into the join points in the base code. Therefore to represent such relationships (or control flow) between an advised module \( m \) (normally a class’s method or constructor) and advice \( a \) (after, before, or around), aspect-weaving edges are used to link the join point shadow nodes within \( m \) to the start nodes, \( s \), of the MCFG corresponding to advice.

**B. Example of AOCFG Construction**

In this section the AOCFG of complete aspect-oriented program, ShadowTracker (Fig. 5) that is referred as \( A \), is analyzed and also shown in the Fig. 7. The ShadowTracker program is composed of 9 modules in the side of base code (in both Point and Shadow classes) which are: Point’s constructor, Shadow’s constructor, getXY(), getXY(), setXY(), setXY(), printPositionP(), printPositionP(), and main() method as well as, one PointShadowProtocol aspect that is consisting of 6 modules. At this moment, assuming the MCFGs of 15 (all together) modules are done and are available. Therefore, based on the aforementioned definitions, the control flow analysis of the ShadowTracker program can be presented as follows:

\[
AOCFG_A = (S^A, E^A, V^A, E^A), \quad \text{where} \quad S^A = 22 \quad \text{and} \quad E^A = 26. \quad \text{Next by referring to (4), we have:} \quad V^A = \bigcup_{k=1}^{9} V_k \bigcup_{p=1}^{1} V^p. 
\]  

The first element in \( V^A \) is a set of all nodes in nine modules in \( A \) program; each represents a call node, statement node, or joint point shadow node. The second element is a set of all nodes in PointShadowProtocol aspect that each represents a pointcut node, call node, or statement node of six modules in given aspect that have been reused. Lastly by referring to (5), we have

\[
E^A = \bigcup_{k=1}^{9} E_k \bigcup_{p=1}^{1} E^p \bigcup \{(23,3), (6,23a),(24,13),(15,24a), (25,16), (18,25a),(54,31),(33,55), (57,24), (60,7), (9,61), (61,19), (21,62), (62,34), (36,63), (63,25), (66,10), (12,67), (67,19), (21,68), (68,34), (36,69), (69,26)\} \bigcup \{(23a,53),(24a,58),(25a,64)\}. 
\]
The first two elements in \( E^1 \) denote the set of all reused edges in the corresponding nine modules and PointShadowProtocol aspect within \( A \) program. The third set is consisting of the inter-module control flow edges from each there is either a call/object creation to a given method/constructor as well as, corresponding return edges \( (E^a) \). For instance, \((54,31)\) represents a Shadow object creation on line 54 that causes a call to the given class’s constructor placed on the line 31. In other words, in the AOCFG a directed edge from call node within the after advice module (line 54) is drawn towards the start node of the Shadow’s constructor MCFG (line 31). Lastly, the fourth set denotes the set of aspect-weaving edges \( (E^a_E) \), for example, \((23a,53)\) represents that there is a join point shadow node named 23a in main () method’s MCFG that is associated with after () advice on line 53 in which setting () pointcut captures any call to the Point class’s constructor. More specifically, Point object creation on line 23 causes a call to the given class constructor that in turn triggers the setting () pointcut, since the given pointcut is associated with the after advice (line 53) therefore the body of advice will be executed. In a nutshell, such flowing of the control between Point’s constructor and advice is represented by \((23a,53)\) edge.

C. The BuildAOCFG Algorithm

Finally, the basic algorithm that can construct the AOCFG for an aspect-oriented program is given below. Fig. 6 shows the pseudo-code of the algorithm, BuildAOCFG.

Algorithm BuildAOCFG
/* generate a control flow graph from the given AO program */

input An aspect-oriented program written in AspectJ: \( A \)
output The aspect-oriented control flow graph of \( \mathcal{A}: \text{AOCFG}_A \)

begin //BuildAOCFG
1. /* preprocess (parse) the aspect-oriented program \( \mathcal{A} \) */
2. for each class C
3. Identify the methods
4. endfor
5. for each aspect A
6. Identify the advice, introduction, pointcut, and method
7. endfor
8. /* build MCFGs for methods in each class and advice, introduction, and methods in each aspect */
9. for each class C
10. GraphMaker(m) //Construct MCFG for each method m in C
11. endfor
12. for each aspect A
13. if A is concrete then
14. for each advice, introduction, or method m declared in A
15. GraphMaker(m) // Construct MCFG for m
16. endfor
17. else
18. GraphTraverser(A)
19. for each advice, introduction, or method m in the extended aspects
20. if m is marked as “inherited” then
21. Reuse module control flow graph (MCFG) from the base aspect
22. end if
23. else
24. GraphMaker(m) // Construct the given MCFG for m
25. endif
26. end for
27. endfor
28. endfor
29. /*connecting MCFGs at call sites in order to build pAOCFG */
30. GraphCombiner()
31. /* weaving MCFGs at join point sites in order to build complete AOCFG */
32. GraphWeaver()
33. /* return the complete AOCFG of \( \mathcal{A} \) */
34. return \( \text{AOCFG}_A \)
end //BuildAOCFG

Fig. 6 Basic algorithm for AOCFG construction

According to algorithm, as input BuildAOCFG gets the source code of the given aspect-oriented program, \( \mathcal{A} \), and as output BuildAOCFG returns the \( \mathcal{A} \)’s control flow graph, which is AOCFG \( _A \). First, BuildAOCFG preprocesses each aspect and class in \( \mathcal{A} \) to get those kinds of information that are necessary for constructing the AOCFG, in this step it identifies advice, introduction, pointcut, and methods (line 1-7). Second, algorithm builds the MCFG for each piece of advice, introduction, and method in aspect or class, using GraphMaker() module. Note that, it builds these MCFGs in a bottom-up fashion according to the aspect and class hierarchies (line 8-28) therefore, to traverse the graph of a given class or aspect a GraphTraverser() module is devised. After that, BuildAOCFG utilizes GraphCombiner() module to connect these MCFGs at the call sites to form the pAOCFG (line 30). Finally, BuildAOCFG builds the complete AOCFG for \( \mathcal{A} \), AOCFG \( _A \), by calling GraphWeaver() module to weave the MCFG at the join points for each piece of advice into the MCFGs for its corresponding methods in the pAOCFG (line 32-34).

The algorithm that is implemented has a class “Controller”, which is the brain of AOCFG Builder tool. It takes in options, and generates constraints (type parameter objects and value parameter objects are collectively known as constraints) for the analysis modules and makes the appropriate calls. The first step in this process is to parse the input source code, and based on this; generate objects representing the options (constraints). After this, the Controller calls the different modules or component in the order specified by the algorithm towards complete construction of AOCFG, and if there are any objects for the modules, it passes them in.

The Controller invokes all other modules in the order specified in algorithm. The following is the module or component invocation order:

1. GraphMaker
2. GraphTraverser
3. GraphAnalyzer
4. GraphCombiner
5. GraphWeaver
6. GraphVisualizer
The details of the components or modules used in this algorithm and their interactions will be discussed in next subsections, whereas each module is responsible for a part of the BuildAOCFG construction process.

D. Graph Maker

GraphMaker has two main functions: building a graph from application code, and adding or removing edges or nodes from a graph (i.e. modifying a graph). This is called filtering a graph. To build a graph, GraphMaker uses the Soot Jimple API [15]. For filtering a graph, the user specifies filters to use on a graph. Filters are also value constraints.

1) Building a Graph: Building a graph is divided into two steps:
   1. Creating nodes
   2. Adding edges between nodes created in step 1

   Each graph type first creates a set of nodes based on the type of graph it is, and these nodes are then passed through a set of value constraints for nodes (i.e. these value constraints
specifically apply to nodes). An example of a value constraints is to only pass nodes that have \( x \) number of parameters.

The next step is to generate edges between the nodes. Each edge, before being added to graph, is passed through a set of value constraints for edges. If an edge fails any of the constraints, it is deleted. It is important to note that, using the node and edge value constraints allows many different alternatives to be run on the same graph type.

2) Filtering a Graph: Filters allow modification of a graph from a holistic point of view. Whereas the constraints only act on a single node or edge at a time, a filter takes in an entire graph and modify it. The modification can depend on the Filter class itself. For example, a filter can remove all nodes with no edges incident to it. These filter objects are the only way to add or remove new edges or nodes form a graph once it has been created. Currently AJeFGraph Builder has 4 different filters.

E. Graph Traverser

GraphTraverser takes in a graph, and generates a set of JGroup based on the types of traversal specified. The following are the three main steps performed by this component or module:

1. Generate a set of starting points for the traversal
2. Traverse the graph once for each starting point and generate a JGroup for that starting point
3. Filter the generated JGroups

1) Generating Starting Points: By default, every node in the graph is used as a starting point. This can be changed by specifying starting point value constraints. Each starting point is used as a node to begin the traversal, and the set of nodes visited by a traversal is added to a JGroup for the starting point. The starting point is always the first element added to the JGroup being generated.

2) Traversing the Ggraph: The type of traversal specifies how a graph is going to be traversed. This is the type constraint for this component. The starting points specify where the traversal begins. Traversing a graph from a starting point is broken into the following three steps:

1. Follow an edge
2. Visit a node and add the node to the JGroup being constructed
3. Add a subset of the edges incident to the node in step 2 to the list of edges to follow

For each traversal, the starting point node is added to a new JGroup. After this, based on the traversal type, a list of edges incident to the starting point is generated. Each of these edges is passed through the following edge value constraints, and if it fails any constraints, the edge is discarded. After an edge passes all the following edge value constraints, the edge is followed and the node at the other end is visited (because the edge can be followed forward or backward, the new node may be the source or destination of the edge). The new node is then passed through adding node value constraints, and if it passes all constraints, it is added to the JGroup, and the edges incident to it are analyzed. If it fails any of the adding nodes’ value constraints, then the node is discarded, and none of the edges incident to it are analyzed.

3) Filtering Groups: Filtering groups is similar to filtering a graph, and represents additional value constraints. This step provides a holistic view of all the groups. This is the only place where groups can be deleted. One important thing to note is that whereas GraphTraverser can only create JGroups, this part of the module can be used to delete either JGroups or VectoredStatistics. In this case, all filters must extend the abstract class FilterGroupConstraints. Examples of filters include deleting groups that are smaller than a certain size, or merging similar groups into a single group.

F. Graph Analyzer

GraphAnalyzer generates VectoredStatistics data structure. VectoredStatistics are generated using the JGroup created by the GraphTraverser. The type constraints define what kind of analysis will be run.

Unlike the other modules, the value constraints for this module are specific to the type constraint. For example, this module can perform clustering, and the value constraint for this is the number of clusters. There are no generic value constraints.

G. Graph Combiner

The function of this component is to take in a number of Graph objects, and create a new graph based on these. This is the only module that allows graphs from different objects (MCFG or pAOCFG) to be analyzed together and combined into a single graph.

More specifically, using the graphs and groups, the algorithm performs an analysis (done by GraphAnalyzer) on the graph and groups and generates a new graph. An example of this is merging all nodes with the same signature (i.e. the signature held in the node element data structure of the given node) from different graphs. This is very useful when different graphs that represent the same code or program are being combined.

Creating a new graph here is very similar to the graph creating steps in GraphMaker. The following are the steps in this component:

1. Create all new nodes
2. Create new edges between nodes

Each new node is passed through a set of value constraints, and if it passes them all, then it is added to a new graph. After all nodes are added, new edges are created, and each new edge is passed through the value constraint for those edges. If the edge passes all of these constraints, then it is added to the graph. Both the creation of nodes and the addition of edges will be dependent on the type of analysis being done.

H. Graph Weaver

The algorithm to build the AOCFG is based on the (static) analysis of the aspect’s pointcut expressions. However, for more complicated join points, it would be necessary to override the code that iterates through an entire method body looking for join point shadows. The overriding code can do
any required analysis of the method body to find instances of the new join points, for instance, one might want to inspect all control flow edges to find the back edges of loops. In particular the algorithm (using GraphWeaver) inserts join point shadow nodes into the MCFG and adds directed edges that link the join point shadow nodes, in all modules, to the advice whose pointcuts picks them up. For each advice, the associated pointcut expression AST tree (obtained from the previous component) is built in order to generate the resulting set of join point shadow nodes related to the statements selected by the pointcuts. Thus, the set of join point shadow nodes which are related to the control flow graph region are picked up by the pointcut declaration [3].

During the traversal of the pointcut expressions, shadow nodes and corresponding edges are added to each MCFG. Each join point shadow node is associated with additional information about the pointcut’s expressions matching it.

More specifically, based on AspectJ code model (or AST) obtained, passes on tree data flow information to check initialization of local variables and the existence of return statements. Again, each AST node implements methods to build the control flow graph for these purposes. The traversal of the AST is performed by the ContextVisitor Polyglot class. The new pass extends ContextVisitor with a method that performs the required action when it encounters a relevant AST node. The following code fragment illustrates the behavior of the new visitor upon entering an AST node:

```java
public NodeVisitor enter(Node parent, Node n){
    if (pass == COLLECT) && n instanceof GlobalPointcutDecl{
        ((GlobalPointcutDecl)n).
            registerGlobalPointcut(this,
                            context(), nodeFactory);
    } return super.enter(parent,n);
}
```

As mentioned above, both new passes are implemented by the same class, and hence the check that pass = = COLLECT makes sure the process is doing the right thing. If the current node is a GlobalPointcutDecl (it is an AST node) so it registers itself with the data structure storing global pointcuts. Then it delegates the rest of work (the actual traversal) to the super class.

I. Graph Visualizer

GraphVisualizer module is responsible for depicting the information obtained from algorithm component on the screen.

The GraphVisualizer takes in a text file in dot format (where the text file represent a graph, G (V,E) produced by the algorithm) and convert it to a visual representation of a graph. To this end, in AJcFgraph Builder implementation, a separate Java graph library called “JGraph” is used [23]. JGraph is the leading Open Source Java Graph Visualization Library. It follows Swing design patterns to provide an API familiar to Swing programmers and functionality that provides a range of features.

In addition, there are value constraints for nodes that can determine which nodes get written out and value constraints for edges that determine which edge get written. In the output, the nodes and edges all have different colors and style, where the different color or styles represent different type of nodes or edges.

VII. DISCUSSION

In order to assess the feasibility and correctness of AJcFgraph Builder some AspectJ software were analyzed and represented by the AOCFG using the proposed tool. Our study used five AspectJ programs taken from AspectJ example package as shown in Table I. The rationale behind was, this collection of programs has also been used as benchmarks by other researchers including [6], [24], [25]. Moreover, for each program table gives the number of aspects, classes, and modules, where module denotes a class constructor, a piece of advice, an inter-type declaration, and a method in either aspects or classes. Note that, since a pointcut does not contain any body code therefore it is not considered as module and consequently does not need any MCFG to represent it.

We verified those AOCFGs generated by the tool against a manual inspection of the graph and the associated analyzed source code for each of aforementioned programs. Our small experiment showed that the AOCFG generated by the tool were correct so that representing AO software by the AOCFG provides a useful support for gaining a better knowledge of the internal structure of these complicated programs, by reducing the effort needed for obtaining them in a variety of software engineering tasks.

Moreover, some user interfaces screenshots of the tool are presented below, which are captured based on the main functionality of AJcFgraph Builder tool.

![Fig. 8 Source code view (after loading)
In this study the AJcFgraph Builder tool, in supporting of the automated construction of AOCFG approach, was proposed. The main features, definitions, and functionalities, as well as its architecture were discussed. The current implementation of tool allows defining, editing, storing and compiling into intermediate code called byte code. Besides, the portability is the other aspect of the given tool that allows easily extension of new type constraints or value constraints. It means, to this end, the related class has to be modified, and the new class must extend the appropriate abstract class, and implement the appropriate methods that need to be implemented.

As future research, the AJcFgraph Builder tool will be improved and evolved to a more mature and scalable tool in order to be used in more complex systems and multi-language aspect-oriented environment. In addition, future work also includes focusing on the given tool to be extended into a quantitative evaluator tool of AO software in which AO metrics are computed, but as part of it the proposed AOCFG and its tool support will be used as underlying basis to develop or adopt existing structural metrics (of OO or procedural) for aspect-oriented paradigm. Also, cost estimation of building representation and graph minimization still remain as open research questions for further research. Furthermore, we are currently working on the given tool to make it as Web-based tool to be online accessible from any corner of the world.

VIII. CONCLUSION AND FUTURE WORK

In this study the AJcFgraph Builder tool, in supporting of the automated construction of AOCFG approach, was proposed. The main features, definitions, and functionalities, as well as its architecture were discussed. The current implementation of tool allows defining, editing, storing and applying AOCFG to an AspectJ system. One of the useful aspects of AJcFgraph Builder is its portability and being run on multiple platforms. The reason is the Java codes are compiled into intermediate code called byte code. Besides, the extensibility is the other aspect of the given tool that allows easily extension of new type constraints or value constraints. It means, to this end, the related class has to be modified, and the new class must extend the appropriate abstract class, and implement the appropriate methods that need to be implemented.

As future research, the AJcFgraph Builder tool will be improved and evolved to a more mature and scalable tool in order to be used in more complex systems and multi-language aspect-oriented environment. In addition, future work also includes focusing on the given tool to be extended into a quantitative evaluator tool of AO software in which AO metrics are computed, but as part of it the proposed AOCFG and its tool support will be used as underlying basis to develop or adopt existing structural metrics (of OO or procedural) for aspect-oriented paradigm. Also, cost estimation of building representation and graph minimization still remain as open research questions for further research. Furthermore, we are currently working on the given tool to make it as Web-based tool to be online accessible from any corner of the world.

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