Improving the structural quality of UML class diagrams with the genetic algorithm

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Abstract. The problem of improving the structural quality of UML class diagrams can be formulated as an optimization problem. The Genetic algorithm is concerned to be able to solve such problems. This paper focuses on the ways in which the Genetic algorithm can be applied to the problem of improving structural quality of UML class diagrams. It develops the theme of semantically equivalent transformations of UML class diagrams during the evolutionary search. This paper suggests the structural semantics of the UML class diagrams. It also formulates the problem of improving the structural quality of a UML class diagram during the evolutionary search and proposes a solution of the problem based on the Genetic algorithm. The paper presents the results of the computational experiment aimed at improving of the structural quality of the UML class diagram with the help of the Genetic algorithm and identifies issues for future work.

1 Introduction

Recent advances in SBSE (Search Based Software Engineering) have provided the possibility of applying evolutionary algorithms to the problems of software engineering, many of which can be formulated as the optimization problems.

The evolutionary algorithm is a bio-inspired algorithm, which iteratively searches for a solution of the problem. The evolutionary algorithms include the genetic algorithm [1], genetic programming [2], simulated annealing [3], swarm intellect [4], bio-geographic algorithm [5], etc.

The Genetic algorithm (GA) is an evolutionary algorithm based on a natural selection mechanism.

A number of studies have investigated different ways of object-oriented software architecture design based on evolutionary algorithms and UML diagram transformations. For example, in [6] hierarchical decomposition of the system has been performed. In [7] pattern based evolutionary transformations have been performed. In [8] authors solve the class responsibility assignment problem with the help of the Genetic algorithm. However, to date it remains unclear which transformations (design patterns, for example) can be automatically performed on the architecture design stage and whether these transformations are semantically equivalent.

The aim of this work is to formalize structural semantics of UML class diagrams and to suggest an algorithm of UML class diagram evolutionary transformation aimed at the improving the diagram structural quality.

The evolutionary transformation of UML diagrams is significant because it allows implementing automatic refactoring of software architecture.

The primary contributions of this paper are:

1. To propose the structural semantics of the UML class diagrams to be able to check equivalence of two UML diagrams.
2. To formalize the problem of improving the structural quality of a UML class diagram during the evolutionary search.
3. To propose a solution of the problem based on the GA.
4. To present the results of the computational experiment aimed at the improving of the structural quality of the UML class diagrams.

2 Structural semantics of the UML class diagrams

In paper [9], the structural semantics of UML class diagrams was suggested. This semantics provides a formal way of describing UML diagram transformations (interface insertion, Façade pattern applying).

Let d be a UML class diagram $d = \{C, I, R\}$, where C is a set of classes $C = \{c_0, c_1, \dots, c_n\}$; I is a set of interfaces $I = \{i_1, i_2, \dots, i_k\}$; R is a set of relations $R = \{r_1, r_2, \dots, r_m\}$.

Then c_i is a class $c_i = \{A_i^i, M_i^i, F_i^i\}$, where A_i is a set of attributes $A_i = \{a_0^i, a_1^i, \dots, a_n^i\}$, M_i is a set of methods $M_i = \{m_0^i, m_1^i, \dots, m_m^i\}$, F_i is a set of features $F_i = \{st_i, v_i, abs_i\}$, st_i is an isStatic feature $st_i \in \{0, 1\}$, v_i is a visibility

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parameter $v_i \in \{public, private, protected\}$, abs_i is an isAbstract feature $abs_i \in \{0, 1\}$.

In addition, i_i is an interface $i_i = \{m_0^i, m_1^i \dots m_m^i\}$ characterized by a set of methods $\{m_0^i, m_1^i \dots m_m^i\}$.

The following kinds of relations r_i are possible between classes: association ($c_1 \rightarrow c_2$), generalization ($c_1 \rightarrow c_2$), aggregation ($c_1 \rightarrow c_2$), composition ($c_1 \rightarrow c_2$), and dependency ($c_1 \rightarrow c_2$), where $\{p_1, p_2\}$ is a power of a relation.

Moreover, the following relations r_i are possible between a class and an interface: realization ($c_1 \rightarrow i_1$) and dependency ($c_1 \rightarrow i_1$).

Now we assume that the structural semantics S_i of the UML class diagram d_i can be described as follows:

$$S_i = \{ \{c_1^i = \{\dots\}, c_2^i = \{\dots\}, \dots c_k^i = \{\dots\}\}, \\ \{i_1^i = \{\dots\}, i_2^i = \{\dots\}, \dots i_l^i = \{\dots\}\}, \\ \{r_1^i, r_2^i, \dots r_m^i\} \}, \quad (1)$$

where S_i is a semantic value of the class diagram d_i ; $c_1^i \dots c_k^i \in d_i$ are the classes of the class diagram d_i ; $i_1^i \dots i_l^i \in d_i$ are the interfaces of the class diagram d_i ; $r_1^i \dots r_m^i \in d_i$ are the relations of the class diagram d_i .

Assume that we are given a UML class diagram $d_1 = \{C_1, I_1, R_1\}$, where C_1 – a set of classes $C_1 = \{c_0^1 \dots c_k^1\}$, I_1 is a set of interfaces $I_1 = \{i_0^1 \dots i_l^1\}$, R_1 is a set of relations $R_1 = \{r_0^1 \dots r_g^1\}$, and the semantic value of d_1 is denoted as S_1 .

Moreover, there is a function $f(d_1)$ evaluating a structural quality of the UML class diagram d_1 .

In addition, we are given a set of semantically equivalent transformations $T = \{t_0, t_1 \dots t_N\}$. An example of such transformation (Interface insertion) is given at Figure 1:

$$S[\{c_1, c_2\}, \{i_1\}, \{c_2 \rightarrow i_1; c_1 \rightarrow i_1\}] \cong \\ \cong S[\{c_1, c_2\}, \{\emptyset\}, \{c_2 \rightarrow c_1\}], \quad (2)$$

where S is a semantic value of the class diagram d ; $c_1, c_2 \in d$ are the classes of the class diagram d ; $i_1 \in d$ is an interface of the class diagram d .

Figure 1. The Interface insertion transformation

Then we can formulate the problem of improving the structural quality of a UML class diagram during the evolutionary search as follows:

It is required to find such a diagram d_2 for n generations with m individuals that:

$$\{d_2 \mid S_{d_1} \cong S_{d_2}; f(d_2) = \min_{d_i} f(d_i)\} \quad (3)$$

In other words, it is required to find such a set of transformations $T^* \in T$, which transfers the d_1 into the d_2 , $d_1 \xrightarrow{T^*} d_2$ that:

$$\{T^* \mid S_{d_1} \cong S_{d_2}; f(d_2) = \min_{d_i} f(d_i)\} \quad (4)$$

3 Solution of the problem based on the GA

In order to use GA, the UML class diagram d_i can be considered as an individual, which corresponds to a chromosome consisting of genes, number of which is equal to the number of classes $C^i \in d_i$. Each of genes stores an information about whether or not the transformation $t_k \in T$ has been applied to a class c_m^i .

This approach is similar to that proposed in [7], where the authors applied design patterns to classes, but our transformation approach includes the essential check of semantic equivalence of the transformation.

Individual mutation occurs by adding/deleting a random transformation to/from a gene.

In order to simplify the representation of UML class diagrams in RAM to process them with the GA, the abstract data structure (ADS) UML Map was proposed [10]. UML Map is based on hash maps; therefore, the evaluation of search complexity is $O(1)$.

A scheme of applying the GA in order to improve the structural quality of the UML class diagram is showed at Figure 2.

Let us formulate $f(d_i)$ in accordance with the Low Coupling principle. For example, we can use a CBO (Coupling Between Objects) metric:

$$CBO_i = \frac{1}{n} \sum_{j=0}^n CBO_{ij}, \quad (5)$$

where CBO_i is an average CBO value of a class diagram d_i with n classes c_j , $j \in 0..n$, which reflects a degree of dependence between the components of the system; CBO_{ij} is a CBO value of the class $c_j \in d_i$, a number of classes connected with c_j except from the dependency relation; n is a number of classes located at the diagram d_i .

Figure 2. Applying the GA in order to improve the structural quality of the UML class diagram

4 Conducting a computational experiment

Suppose we are given a UML class diagram 'E-commerce' d_1 , which is showed at Figure 3. Its semantic value S_1 is as follows:

$$\begin{aligned}
 S_1 = & \{ \{c_1, \dots, c_{17}\}, \{\emptyset\}, \{c_{17} \xrightarrow{\text{aggreg}} c_8; c_2, c_5, c_6 \xrightarrow{\text{comp}} c_1; \\
 & c_{11} \xrightarrow{\text{comp}} c_3; c_{12} \xrightarrow{\text{comp}} c_7; c_{17} \xrightarrow{\text{comp}} c_{10}; c_{16} \xrightarrow{\text{comp}} c_{14}; \\
 & c_2, c_5, c_6, c_{13} \xrightarrow{\text{gener}} c_9; c_2, c_7, c_8, c_{10}, c_{14} \xrightarrow{\text{gener}} c_4; \\
 & c_{11}, c_{12}, c_{16}, c_{17} \xrightarrow{\text{gener}} c_{15}; c_2, c_5 \xrightarrow{\text{dep}} c_3; c_6, c_8, c_{13} \xrightarrow{\text{dep}} c_7; \\
 & c_{13} \xrightarrow{\text{dep}} c_8; c_9 \xrightarrow{\text{dep}} c_{10}; c_5, c_9 \xrightarrow{\text{dep}} c_{14} \} \}
 \end{aligned} \quad (6)$$

A computational experiment has been conducted with the number of individuals in population = 200, the probability of mutation = 0.5, the percentage of crossover participants = 25%. The attained dynamics of $f(d_1)$ is showed at Figure 5.

Figure 3. The null-diagram d_1 'E-commerce'

Figure 4. The dependence of $f(d_1)$ values from the iterations count

On the 100 000th iteration has been achieved an individual d_2 with the lowest value of $CBO=0.941$, which is showed at Figure 5. The semantic value S_2 of the d_2 is as follows:

$$\begin{aligned}
 S_2 = & \{ \{c_1, \dots, c_{17}\}, \{i_1, \dots, i_4\}, \{c_{17} \xrightarrow{\text{aggreg}} c_8; c_2, c_5, c_6 \xrightarrow{\text{comp}} c_1; \\
 & c_{11} \xrightarrow{\text{comp}} c_3; c_{12} \xrightarrow{\text{comp}} c_7; c_{17} \xrightarrow{\text{comp}} c_{10}; c_{16} \xrightarrow{\text{comp}} c_{14}; \\
 & c_2, c_5, c_6, c_{13} \xrightarrow{\text{gener}} c_9; c_2, c_7, c_8, c_{10}, c_{14} \xrightarrow{\text{gener}} c_4; \\
 & c_{11}, c_{12}, c_{16}, c_{17} \xrightarrow{\text{gener}} c_{15}; c_2, c_5 \xrightarrow{\text{dep}} i_1; c_6, c_8, c_{13} \xrightarrow{\text{dep}} i_2; \\
 & c_{13} \xrightarrow{\text{dep}} i_3; c_9 \xrightarrow{\text{dep}} c_{10}; c_5, c_9 \xrightarrow{\text{dep}} i_4; c_3 \xrightarrow{\text{real}} i_1; c_7 \xrightarrow{\text{real}} i_2; c_8 \xrightarrow{\text{real}} i_3; \\
 & c_{14} \xrightarrow{\text{real}} i_4 \} \}
 \end{aligned} \quad (7)$$

Applying the rule (2) to the expression (7), we attain:

$$\begin{aligned}
 S_2 = & \{ \{c_1, \dots, c_{17}\}, \{\emptyset\}, \{c_{17} \xrightarrow{\text{aggreg}} c_8; c_2, c_5, c_6 \xrightarrow{\text{comp}} c_1; \\
 & c_{11} \xrightarrow{\text{comp}} c_3; c_{12} \xrightarrow{\text{comp}} c_7; c_{17} \xrightarrow{\text{comp}} c_{10}; c_{16} \xrightarrow{\text{comp}} c_{14}; \\
 & c_2, c_5, c_6, c_{13} \xrightarrow{\text{gener}} c_9; c_2, c_7, c_8, c_{10}, c_{14} \xrightarrow{\text{gener}} c_4; \\
 & c_{11}, c_{12}, c_{16}, c_{17} \xrightarrow{\text{gener}} c_{15}; c_2, c_5 \xrightarrow{\text{dep}} c_3; c_6, c_8, c_{13} \xrightarrow{\text{dep}} c_7; \\
 & c_{13} \xrightarrow{\text{dep}} c_8; c_9 \xrightarrow{\text{dep}} c_{10}; c_5, c_9 \xrightarrow{\text{dep}} c_{14} \} \}
 \end{aligned} \quad (8)$$

From (8) it follows that $S_1 \cong S_2$, so the obtained diagram d_2 is semantically equivalent to the diagram d_1 .

Figure 5. The diagram d_2 attained on the 100 000th iteration

5 Discussion

The results presented here demonstrate that GA has a potential to conduct automatic refactoring of UML class diagrams, but further studies are needed.

The limitation of the present research is that the only one type of transformations has been applied. The rate of the convergence might have decreased if the experiment had been carried out with a significantly larger set of transformations T^* and it would be beneficial to investigate this further [11].

In addition, the current study did not investigate the qualitative effect of different transformations on the values of various structure quality parameters.

6 Conclusions

In this work, we have formalized the structural semantics of UML class diagrams and the semantically equivalent transformations. In addition, we have formalized the problem of improving the UML class diagram structural quality.

We have proposed a solution of the problem based on the GA and on the UML Map data structure.

The study indicates that it is possible to perform automatic refactoring of UML class diagrams using semantically equivalent transformations. The results of this research can serve as a basis for further studies into evolutionary UML diagram transformations.

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