Automatically detecting the conflicts between software requirements based on finer semantic analysis

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Abstract

Context: Conflicts between software requirements bring uncertainties to product development. Some great approaches have been proposed to identify these conflicts. However, they usually require the software requirements represented with specific templates and/or depend on other external source which is often uneasy to build for lots of projects in practice.

Objective: We aim to propose an approach Finer Semantic Analysis-based Requirements Conflict Detector (FSARC) to automatically detecting the conflicts between the given natural language functional requirements by analyzing their finer semantic compositions.

Method: Firstly, we build a harmonized semantic meta-model of functional requirements with the form of eight-tuple. Then we propose algorithms to automatically analyze the linguistic features of requirements and to annotate the semantic elements for their semantic model construction. And we define seven types of conflicts as long as their heuristic detecting rules on the ground of their text pattern and semantical dependency. Finally, we design and implement the algorithm for conflicts detection.

Results: The experiment with three different open requirements datasets shows that our semantic analyzing algorithms can correctly identify about 94.93\% elements of software requirements in average. And the other experiment with four requirement datasets illustrates that the recall of FSARC is nearly 100\% and the average precision is 83.88\% on conflicts detection.

Conclusion: We provide a useful tool for detecting the conflicts between natural language functional requirements to improve the quality of the final requirements set. Besides, our approach is capable of transforming the natural language functional requirements into eight semantic tuples, which is useful not only the detection of the conflicts between requirements but also some other tasks such as constructing the association between requirements and so on.

Keywords: Software requirement specifications, Requirements conflict, Semantic requirement metamodel, Semantic elements labeling

1. Introduction

Software requirements, especially of the large and complex projects, are usually from massive stakeholders with diverse background and interests \[38\]. Conflicts among software requirements are therefore inevitable due to their different views and concerns. Besides, requirements are continually changing \[26\]. Conflicts occur during the whole life-cycle of software product. Actually, some researches show that a very high number of conflicting requirements was identified among software projects in practice \[46\], \[41\]. Egyed and Grünbacher \[21\] pointed out that “requirements conflict with each other if they make contradicting statements about common software attributes …”. Given that there may be up to \(n^2\) conflicts among \(n\) requirements …, the number of potential conflicts, …, could be enormous, burdening the engineer with the time-intensive and error-prone task of identifying the true conflicts”. And Mai-riza et al. \[31\] reported that the ratio of conflicting requirements is from 40\% to 60\%. The conflicts between requirements cause the project cost overrun \[50\], \[57\] and failure \[10\]. However, detecting the conflicts of requirements is one of the most important but yet one of the most challenging aspects of requirements validation \[17\], \[37\], \[51\].

The current methods of detecting requirements conflicts can be divided into two categories: manual walk-through and automatic detection. The first stream of manual approaches, such as the win-win requirements negotiation approach \[8\] and its variant easy-win-win \[9\], are very common in practice. However, many experts with enough domain knowledge are usually involved and need to spend tedious time on it. The manual identification is therefore “time-intensive and error-prone” \[21\]. Relatively speaking, the automated genre can save human efforts to a certain degree \[21\]. However, most of these approaches need the requirements with specific format such as the extended Bakkus-Naur-Form (EBNF\[36\]) and the Semantic Application Design Language (SADL) \[35\]. Besides, some other artifacts beyond requirement specifications are required such as executable code \[21\], system performance constraints \[48\] which are usually unavailable especially in the early phrase of projects.

In addition, the conflicts under analysis in these research are...
different, including redundant requirements \[48\], conflicting or incomplete requirements \[45\] and so on. And it is necessary to build an harmonized view about the conflict types.

The final goal of this study is to automatically detect the conflicts between natural language functional requirements. We regard natural language as the requirement format of our study, since 71.8% of the requirement documents are written in natural language in engineering practice\[30\]. Natural language requirements may have variety of forms, including modal verb-style statements (such as shall- or will- style), use cases, user stories and feature lists \[39\]. And shall-style statements are very commonly used to specify requirements in industry \[49\]. Besides, we mainly concern ourselves with functional requirements which may have their related constraints in resource limitation, access time and so on, since they are the base of software design and development. And the constraint from non-functional requirements need to be satisfied through the implementation of functional requirements. So in the remainder of this study, requirements mean a set of NL shall-style statements on the functionality of the system or system components.

In order to achieve our goal, we propose an approach of a Finer Semantic Analysis-based Requirements Conflict Detector (FSARC) to identify seven types of conflicts among functional natural language requirements based on analyzing and detecting their finer semantical components. To be specific, we firstly build a semantic meta-model of software requirements denoting the semantic elements of functional requirements. Then we design heuristic rules and algorithms for automatically identifying these elements based on the natural language processing results such as part-of-speech (POS) and the semantic dependency parsing (SDP). Finally, we define seven types of conflicts on the ground of analyzing the existing research and detecting them based on a set of predefined rules.

Our contributions are therefore threefold:

1. We provide a harmonized view of the semantic meta-model of software functional requirements, and propose an approach of automatically identifying the related elements from NL requirements.
2. We define seven types of conflicts among requirements with three categories through carefully analyzing the related literatures, and propose an approach of automatically detecting them.
3. The two automated approaches for semantic elements identification and conflicts detection respectively were evaluated with more than three open requirement sets. And the results show the great performance of our approaches. We public the source code of these two algorithms via Github \[https://github.com/GuoWeize/FSARC\].

We organize the structure of this present paper as follows. Section 2 introduces the background on the general definition of requirements conflict and the related work on the detection of requirements conflict. Section 3 describes the framework of our approach FASRC. Then Section 4 and 5 illustrate the two parts of FASRC including the semantic elements detection of software requirements and the conflicts detection between them. In the end of each section we introduce the related evaluation experiments and the results. In Section 6 we discuss the threats to validity of this study. In the end, the conclusions of this work and the future work plan are given in Section 7.

2. Background and the related works

2.1. The general definition of requirements conflicts

In the field of requirement engineering, the term conflict involves inference, interdependency, and inconsistency between requirements \[19\]. Kim et al. \[28\] regarded requirements conflicts as “the interactions and dependencies between requirements that can lead to negative or undesired operation of the system”. Alberto et al. \[45\] believed that “when a crosscutting requirement has a negative contribution with another crosscutting requirement in the same base requirement, a conflict between aspect-oriented software requirements occurs”. Cameron et al. \[11\] regarded requirements conflicts as “unexpected or contradictory interaction between requirements that has a negative effect on the results”.

From the perspective of conflicting objects, the conflicts may exist between the requirements of the same or different types, such as between functional requirements \[7\], between functional and non-functional requirements \[21\], and between non-functional requirements \[43\]. Also conflicts can exist between two different manifestations of the same requirement, such as between textual term and use case graph \[27\], between textual term and table form \[44\], and so on.

In this study, we focus on the semantical conflicts among different textual functional requirements, which means that the inference, interdependency and any other relationship between requirements can lead to inconsistency. For instance, the duplication of two requirements may cause inconsistency when one requirement is changed while another not.

2.2. The NLP technologies used in this study

The natural language processing (NLP) technologies are used to aid analyzing and understanding the human language. It involves lexical and syntactic analysis to obtain the meaning of the strings of symbols in natural language conforming to the rules of formal grammar. In this study, we would like to analyze the structure and meaning of textual functional requirement statement, helping detect conflicts further. With the help of NLP, we are able to identify the semantic elements of requirement statement through analyzing their grammar and syntactic structures, and to build the mapping rules between these structure units and the semantic elements.

We mainly use Part-Of-Speech (POS) tagging and Dependency Parsing (DS), especially Semantic Dependency Parsing (SDP). POS is to mark each word with a correct part of speech, that is, to determine whether the word is a noun, a verb, an adjective or others. SDP is to analyze the binary semantic relationship between the language units (i.e., word or phrase) of one sentence, for instance, a nsubj (subject to predicate) relationship existing from “like” to “I” in the sentence “I like it.”.
CoreNLP [32], proposed by Stanford University, is one of the most popular NLP tools, providing many kinds of basic analysis for several languages, including POS tagging, parsing tree analysis, dependency relationship analysis and so on. And most of its POS and SDP analysis results are followed the definitions of Universal Dependencies[11]. Basic POS tags include N(noun), V(verb), ADJ( adjective), ADV(adverb) and so on. Basic dependencies in SDP include nsubj(subject to predicate), dobj(predicate to direct object), root(root to predicate) and so on. And other dependencies are mainly about the relation between modifier, qualifier and clause. We firstly pre-process textual requirements by CoreNLP, and then combine the results of POS and SDP to obtain a comprehensive view of their semantic roles.

2.3. Related works on requirements conflict detection

Detecting the conflicts between software requirements has always been a hot topic in software engineering, and there have been a few pretty good studies.

Egyed and Grünbacher [21] detected the cooperating and conflicting relations between natural language requirements based on the trace dependencies among requirements, with the usage of a tool-supported trace analysis technique [20]. Besides the NL requirements, they also need the associations between requirements and test scenarios as the input.

Kim et al. [28] require requirements described in goals and scenarios using the authoring structure, which contains Action (Verb) + Object (Object) + Resource (Resource). They can automatically detect two types of conflicts which are syntactic conflict meaning requirements conflicts according to a predefined condition, such as “Different Verb \( \cap \) Same object”, “Same Verb \( \cap \) Different Object”, or “Same Resource”, and semantic conflict including activity conflicts and resource conflicts.

Moser et al. [36] proposed an ontology-based approach OntReq to detect three types of conflicts: conflict between requirements (CRR), conflict between a requirement with a constraint (CRC), conflict between a requirement with a formal guideline(CRG), i.e., ill-formed requirement. They require functional requirements and constraints, including technical constraints, requirement constraints, documentation guidelines and glossary as inputs. And functional requirements must follow the EBNF template, specifying under which conditions a target system should provide a certain functionality regarding a specific object to a certain entity or role.

Ali et al. [4] applied SAT-based techniques [17] to automatically check the consistency between contextual requirements and the consistency between executable tasks. They require requirements represented by a contextual goal model, which is the environment in which the system operates. And they defined two conflict types: conflicting changes (many processes try simultaneously to change the same object into different states) and exclusive possession (processes need an exclusive possession of an object).

Chentouf [13] require requirements in a controlled natural language derived from KAOS [16]. He focused on three conflict types: duplicated requirement (two requirements being exactly the same or one being included in the other), incompatible requirements (two requirements are ambiguous, incompatible, or contradictory), assumption alteration (the output of one requirement’s operation is part of the inputs or outputs of the other’s operation). Unfortunately, this work doesn’t include an automated approach or the critical detection algorithms.

Salado and Nilchiani [44] traced requirements to stakeholders’ needs, and automatically constructed the tension matrix (including resources, phases of matter, laws of physics, laws of society, and logical contradictions) to identify potential conflicting requirements. Based on the tension matrix, they defined five conflicts types from resources, phases of matter, laws of physics, laws of society and logical contradictions. Their method is particularly effective for the requirements containing quantitative numbers.

Walter et al. [48] formalized NL requirements into conjunctive normal form (CNF) using specification pattern systems (SPS), linear temporal logic (LTL) and first order logic (FOL) semi-automatically. They only focus on redundant requirement specifications.

Moitra et al. [35] need the requirements specified with Semantic Application Design Language (SADL) [15]. They perform formal analysis using ACL2 Sedan tool [12] automatically and resolve errors during the requirements authoring process. According to their formal rules, they only detect conflicting or incomplete requirements.

From the above simple survey, we can make the following observations:

- The input formats of requirements can be mainly divided into two categories: in natural language and in specific format, usually constraint format. Given that most software requirements are in natural language in practice [39], the approaches with specific formal format need more transforming work for practical purposes. However, the transforming work is often unavailable.

- Many methods require external data to assist or promote requirement formalization and inconsistence detection, such as the tracing between requirements and test scenarios [20], glossary [36] and stakeholder’s needs [44]. However, some data is usually hard to acquire, even unavailable [66].

- These work focus on different kinds of conflicts from diverse perspectives, although with small portion of overlapping.

- Only [13] and [44] provide public dataset. Unavailable data causes inconvenience of the work reproducing and testing.

https://universaldependencies.org/
3. FASRC: Finer Semantic Analysis-based Requirements Conflicts Detector

Our approach FASRC for requirements conflict detection involves two phases, which are semantic element identification (Phase I) and conflicts detection (Phase II). The procedures of our approach is shown in Figure 1.

In the first phase, we identify the finer semantic elements of NL requirements. For this purpose, the semantic requirement meta-model defining the common compositions of the semantic elements is required. Thus, we firstly provide an harmonized view of the semantic requirement meta-model through analyzing the existing literatures and part of the requirement set (in Step ①). Then, we propose an algorithm for identifying the semantic elements for each requirement (in Step ②). In other words, we annotate the requirements with their semantic elements automatically. The core step is to discover and build the mapping rules between the grammar and semantic elements of requirements. To implement this, we manually annotated the semantic elements of a random requirement set of Unmanned Aerial Vehicle (UAV) from the University of Notre Dame [14], and looked up their grammar elements on the ground of POS and SDP generated by Stanford CoreNLP [32]. We analyzed the mapping between the manual annotations and the NLP results, and built the rules, which are the key part of our semantic annotating algorithm.

In the second phase, we detect the conflicts between requirements based on their finer semantic elements annotation. Obviously, the formal definition of our focused conflicts is the prerequisite for the conflict detection. We define seven conflict types with three categories in this study (in Step ③). Finally, we propose our conflict detection algorithm by defining the rules upon the conflict definition and the semantic annotations of requirements (in Step ④).

4. Phase I: Automatically identify the finer semantic elements of NL requirements

4.1. Our semantic metamodel of functional requirements

There are some existing semantic models of requirements. Kim et al. [28] proposed that requirement statements can be described with goals and scenarios authoring structure, which contains Action (Verb) + Object + Resource. Rupp et al. [42] proposed an EBNF template of requirements specifying under which conditions (under condition) a target system should provide a certain functionality (process) regarding a specific object (thing to be processed) to a certain entity or role (somebody or something). Chentouf [13] proposed that requirement statements can be formally described as eight tuples including the ID, the effect of requirement (i.e., start, stop, or forbid an operation), the trigger, agent, operation, input, output, and the waiting time for the periodical execution of operation.

We prefer Chentouf’s model because they give finer elements such as the input, output and the execution frequency. However, there are three points which can be improved:

- Although the effect of requirements (i.e., start, stop or forbid an operation) can explicitly tell whether two requirements are conflict or not on the state, they didn’t give the way of specifying this effect. Besides, it is redundant to the operation semantically.
- They only describe the operation frequency of the operation. However, there are much more restriction about the operation such as the execution sequence and resource limitation.
- They didn’t give formal definition of these eight tuples but in natural language only. This brings ambiguity. For example, the input is constituted by the set of objects, but the definition of object is unmentioned.

We therefore present our novel eight-tuple: \{id, groupId, event, agent, operation, input, output, restriction\}. The specific definition is as follows:

- id: The identifier of the requirement, usually consisting of numbers and/or letters. The id of each requirement should be unique.
- groupId: For the sake of simplicity, we expect one requirement contains only one operation. Thus, we reorganize the requirements with multiple predicate and split them into several associated requirements of the same group with the same groupId, agent and event. The groupId is a natural number.
- event: The timing or trigger condition of one requirement. When event is satisfied, agent must perform the operation. We find that event is usually a complete sentence (i.e., adverbial clause), like the requirement statement, but without id, groupId and event. Therefore, we use five-tuple: \{agent, operation, input, output, restriction\} to describe the semantic elements of event. If there are multiple conditions in one single requirement, five-tuple of all events are connected by “and” or “or”, which depends on the conjunction between two events.
- agent: The executor of operation, usually the real subject of the main clause of the requirement.
- operation: The core action of the requirement, also the predicate of the main clause of the requirement. The action is usually depicted with a verb and sometimes contains other supplements like to do.
- input: All the data that already exists before, which needs to be used when the operation is executed.
- output: All objects that can be created, destroyed, or altered after executing the operation.
- restriction: Constraint is on performing the operation, which can be the execution time, place, frequency, execution sequence, and some other restriction such as resource and its quantity.
To make it easy to understand, we give an example of the eight-tuple of a requirement of UAV in Figure 2. In this example, we annotate the event, agent, operation, input, output and restriction. The id and groupId rely on other requirements in the whole set and we don’t list them here.

When a flight plan is activated for a UAV on the ground, the FlightScheduling shall send the UAV a takeoff message in one second.

Figure 2: The eight-tuple of one requirement example in UAV set

We find that agent is a nounal structure, usually a noun. Sometimes there are some modifiers to give the indispensable supplement of the nounal structure. The modifiers may include adjective word, adjective clause, determiner, quantifier and so on. Also, the subordination between this and another nounal structure is included in the modifiers, since it specifies the nounal structure too. And input and output are both consisted of a series of nounal structures. For convenience of formalization, we define a structure called entity, which denoted the nounal structure above. Therefore, agent is an entity, input and output are sets of entities.

To facilitate automatically identifying the semantic tuples, we present the definition of eight-tuple in the form of BNF as follows:

\[
\begin{align*}
\text{agent} & ::= \emptyset | \langle \text{entity} \rangle \\
\text{operation} & ::= \langle \text{operation\_mode} \rangle \langle \text{predicate} \rangle \\
\text{input} & ::= \langle \text{entity\_set} \rangle \\
\text{output} & ::= \langle \text{entity\_set} \rangle \\
\text{restriction} & ::= \emptyset |\langle \text{string} \rangle^* \\
\text{letter} & ::= \langle \text{string} \rangle^* \\
\text{digit} & ::= \langle \text{string} \rangle^* \\
\text{string} & ::= \langle \text{digit} \rangle\langle \text{letter} \rangle \\
\text{condition} & ::= \langle \text{agent} \rangle \langle \text{operation} \rangle \langle \text{input} \rangle \langle \text{output} \rangle \\
\text{restriction} & ::= \emptyset |\langle \text{string} \rangle^* \\
\text{conj} & ::= \langle \text{string} \rangle^* \\
\text{entity} & ::= \langle \text{modifier} \rangle \langle \text{base} \rangle \\
\text{modifier} & ::= \emptyset |\langle \text{string} \rangle^* \\
\text{base} & ::= \langle \text{string} \rangle \\
\text{operation\_mode} & ::= \emptyset | \langle \text{ABLE} \rangle | \langle \text{NOT} \rangle \\
\text{predicate} & ::= \langle \text{string} \rangle \\
\text{entity\_set} & ::= \emptyset |\langle \text{entity} \rangle^* \\
\text{event} & ::= \emptyset |\langle \text{condition} \rangle \langle \text{conj} \rangle \langle \text{condition} \rangle
\end{align*}
\]

According to the above BNF items, one requirement is an eight-tuple. Event is usually a single clause depicting the condition, but if there are multiple conditions in a single requirement, they should be connected by conj ("and" or "or") based on the conjunction between them. And event is labeled as "ALL" when no actual event can be found in a requirement, which means the operation can be executed under any circumstance. Given that conflict detection upon clauses are not easy since clause is usually composed of a couple of semantic units, we represent the condition as five-tuple. Operation is a string of core verb with a specific operation\_mode: "ABLE", "NOT" or the default mode, and we will specify them in Section 4.2.1. The agent, input and output are composed of noun words/phrases and their modifiers. For the convenience of describing these tuples, we refer the noun word/phrase (base) and all of its modifiers as entity. Restriction is defined as a set of string and each string denotes a single constraint.
4.2. Automatically identifying the finer semantic elements

In general, our algorithm is based on heuristic rules and we adopt the divide and conquer principle during the algorithm design. Since each semantic element is distinctive, we propose different algorithms to identify them. The pseudo-code description of our main algorithm is given below in Alg. 1.

```
Algorithm 1: MainAlgorithm
Input: requirement (one NL requirement entry), id, groupId
Output: requirement_tuple (eight-tuple)
/* Use POS and SDP to parse requirement statement */
1 if the requirement has multiple predicate verbs then
   /* Divide it into multiple requirements */
   sentence_group = SentenceSplit(requirement)
   groupId = groupId + 1
   /* Modelling each divided requirement */
   for each sentence ∈ sentence_group do
      r = MainAlgorithm(sentence, id, groupId)
   end
/* Extract each tuple from the clause */
operation = OperationParse(requirement, pos, dependencies)
agent = AgentParse(operation, dependencies)
restriction = RestrictionParse(requirement, pos, dependencies)
requirement_tuple = [id, groupId, event, agent, operation, input, output, restriction]
return requirement_tuple
```

**Heuristic rules construction** For identifying each of the elements, except the id, we need to construct the extraction rule firstly. To be specific, we randomly selected 50 requirements from the UAV set. The first two authors manually annotated their semantic elements independently and discussed the discrepancies to form an agreement on the final annotations. Then we run CoreNLP[32] and generated POS as well as SDP results of these requirements. We recorded and analyzed the mapping between each semantic elements of each annotated requirements and their grammar elements. Finally we gave the heuristic rules of identifying each semantic element from the NL requirements.

During the analysis, we have three findings about the NL requirements, which can be confirmed by work [49]:

(a) The predicate appears after the modal verb, including words such as “shall”, “must”, “can”.

(b) The conditional adverbial clause usually begins with the word “when” or “if”.

(c) The pronoun words, such as “it” or “them”, usually do not appear in NL requirements.

We assume that the NL requirements satisfy the above three conditions. For the very few requirements violating them, we manually adjust the statements before running our algorithm to identify the semantic elements.

In the following sections, we introduce the heuristic rules and the related identification algorithm for each of the semantic elements, in line with the sequence in Alg. 1:

4.2.1. Identifying the Operation

Operation is the core action that agent should execute, and is usually the predicate of the main clause of NL requirement. Among all of the semantic elements, the operation identification is the easiest since the Shall-style statements have very obvious feature about the position of predicate verb. Therefore our algorithm starts from the operation.

During the requirement work-through, we find that there are different execution timing of operation. Some requirements are with the phrases like “have the ability to do something”. That means, when the triggering event occurs, operation may not be executed, instead, it only has the possibility of execution. And some requirements contain the phrases like “not do something”, that is, when the event occurs, operation should not be executed. Other requirements are with the meaning of “should do something”. That means, when the event occurs, operation should be executed. Therefore, we define three types of operation mode: ABLE, NOT and the default.

The rules for identifying the operation are as follows:

(a) The predicate verb in the main clause should become operation.

(b) The operation should belong to one of the above three categories and the rules for identifying these categories are as follows:

(i) If requirements’ main clauses contain any directive, such as “enable”, “be able to” and so on, operation mode should be ABLE. For instance, the operation of the requirement “The DronologyRuntimeMonitor shall be able to receive messages from any Dronology component” is “ABLE receive”. 

(ii) If requirements’ main clause contains a negative word, such as “not”, before the predicate verb, operation mode should be NOT. For instance, the operation of “When a UAV has an active onboard Obstacle Avoidance, the ObstacleAvoidance system shall not issue directives” is “NOT issue”.

(iii) Other requirements’ operation mode is the default form.

(c) The infinitive structure directly related to the predicate verb of the main clause can be considered as the complement to it, since it usually expresses the purpose of operation. Therefore, the infinitive structure should be included in operation. For instance, for the requirement
“The RouteCreationUI shall allow a user to delete a route”, the operation is “allow to delete”.

(d) Some requirements are with copula verbs, usually “be” and predicative. The composition of “be” and predicative is regarded as operation with the purpose of expressing the relatively complete semantic. Also the predicative determines the condition of agent. For instance, the operation of “Only one instance of each registered drone shall be active at any time” is “be active”.

The algorithm for operation identification based on the above rules is depicted in Alg. 2.

Algorithm 2: OperationIdentification

Input: clause (single requirement entry), pos (result of POS), dependencies (result of SDP)
Output: operation
1 if “shall” ∈ clause or “must” ∈ clause then
2 operation = the word following “shall” or “must”
3 else if “can” ∈ clause or “may” ∈ clause then
4 operation = the word following “can” or “may”
5 operation.operation_mode = ABLE
6 /* If the first word of the clause is past participle or present participle of a verb, the verb is operation */
7 else if pos[first_word] == VBN or VBG then
8 operation = the first word of this clause
9 /* If ‘be’ appears, the clause is SVC format or passive voice */
10 else if “be” ∈ clause then
11 if ∃ dep ∈ dependencies satisfies: (dep.type = cop and dep.end == “be”) then
12 operation = link verb + copula
13 else if pos(word following “be”) == VBN then
14 operation = word following “be”
15 end
16 /* If the clause has an infinitive structure directly related to predicate verb of the main clause */
17 if ∃ dep ∈ dependencies satisfies: (dep.type = xcomp and dep.start == operation and dep.end == “to” and pos(word following “to”) == VBD) then
18 operation = operation + “to” + word following “to”
19 end /* If there is a negative word in the clause */
20 if ∃ dep ∈ dependencies satisfies: (dep.type = neg and dep.start == operation) then
21 operation.operation_mode = NOT
22 end
23 return operation

4.2.2. Identifying the Agent

Agent is the executor of operation, and is usually the real subject of the main clause. The rules for identifying the agent in NL requirements are as follows.

(a) For the requirements described in active voice, the real executor of the operation is the sentence subject. So the noun that has nsubj dependency with the predicate verb of the main clause should become agent. Note: nsubj from the SDP results of CoreNLP [13], means nominal subject.

(b) For the requirements described in passive voice,
(i) If there is a noun after “by”, the noun is regarded as the agent. Note that the noun here may be single word or phrase.
(ii) If there is no noun after “by”, we denote agent as ∅, meaning that any entity can be the agent.

The algorithm upon these rules is listed in Alg. 3.

Algorithm 3: AgentIdentification

Input: operation, dependencies
Output: agent
1 if the requirement is passive voice then
2 if ∃ dep ∈ dependencies satisfies: (dep.type == dep and dep.end == “by”) then
3 /* The agent is the real subject of the sentence */
4 agent = EntityParse(dependency.start, dependencies)
5 else /* If real subject is not found, the agent is any entity */
6 agent = ∅
7 end /* The noun with nsubj dependency of predicate verb with the main clause should become agent */
8 if ∃ dep ∈ dependencies satisfies: (dep.type == nsubj and dep.start == operation) then
9 agent = EntityParse(dep.end, dependencies)
10 end
11 return agent

4.2.3. Identifying the Event

Event is the precondition or trigger(s) of a requirement. It is usually the abverbal clause of condition of the sentence.

For the sake of identifying the conflicts related with event, we divide the event clause into finer five-tuple: {agent, operation, input, output, restriction}. The approach of identifying these elements are same with that of annotating the agent, operation, input, output and restriction in NL requirement.

We made three rules for the automated event identification.

(a) The conditional adverbial clause starting with specific connective words, such as “when” or “if”, if existing, is the event of the requirement. And the clause begins with one connective word and ends with one specific punctuation, such as comma, period and semicolon.
(b) If there are at least two conditional adverbial clauses, and these clauses are connected with “and” or “or”, the event should also includes multiple parts connected with “and” or “or”.

(c) If there is no conditional adverbial clause, event should be marked as ∅, meaning the requirement can be executed under any circumstances.

The event identification algorithm is depicted in Alg. 4.

### Algorithm 4: EventIdentification

- **Input:** clause (single requirement entry), the phrases of agent
- **Output:** the phrases of event

```python
if there are “when” or “if” in clause then
event_clause = the portion from “when” or “if” to agent of clause
(pos, dependencies) = CoreNLPResolve(event_clause)
event.operation = OperationParse(event_clause, pos, dependencies)
event.agent = AgentParse(event.operation, dependencies)
(event.input, event.output) = InputOutputParse(operation, dependencies)
event.restriction = RestrictionParse(event_clause, pos, dependencies)
return (event.agent, event.operation, event.input, event.output, event.restriction)
else
    return ∅
```

4.2.4. Identifying the Input & Output

Input is all of the data that already exist before, and is required by operation for its execution. Output is all of objects that can be created, destroyed or altered after executing the operation. These two elements are identified at the same time because they are always intertwined with each other in the requirement statements.

We gave five rules for the automated input & output identification.

(a) The direct object of the predicate verb of the main clause should be included in input and output. In SDP, the relation between predicate and its direct object is dobj. The direct object is usually the core object altered during the operation execution. For instance, for requirement “When a flight plan is executed, the VehicleCore shall send the next waypoint to the UAV”, the direct object is “the next waypoint”.

(b) If a requirement statement is in passive voice, its formal subject should be included in input and output. Typically, the formal subject is recognized as the subject of active voice requirement, that is, the noun that has nsubj dependency with the predicate verb. For instance, in requirement “When the RealTimeFlightUI is loaded, a map shall be displayed”, the formal subject is “a map”.

(c) Nouns and noun phrases in the preposition-object compound and adverbial components should be included in input, since these nouns are also used during executing operation. And they are identified by nmod dependency, excluding nmod:by, nmod:poss, nmod:of and nmod:at. For instance, input of the requirement “The RealTimeFlightUI shall allow users to follow one or multiple UAVs on the map” are “one or multiple UAVs”.

(d) If there is no entity in input or output, it should be denoted as ∅.

The algorithm based on these rules for input & output identification is given in Alg. 5.

### Algorithm 5: InputOutputIdentification

- **Input:** operation, dependencies
- **Output:** input, output

```python
if clause is passive voice and direct object of predicate verb /
if clause is passive voice and ∃ dep ∈ dependencies satisfies:(dep.type == nsubjpass and dep.start == operation or dep.type == dobj and dep.start == operation) then
    entity = EntityParse(dependency.end, dependencies)
    input = input ∪ {entity}
    output = output ∪ {entity}
end
for all dep ∈ dependencies do
    if dep.type == nmod and dep.type ≠ nmod:poss, nmod:of, nmod:agent, nmod:by then
        entity = EntityParse(dep.end, dependencies)
        input = input ∪ {entity}
end
return (input, output)
```

4.2.5. Identifying the Restriction

Restriction is the constraints on the operation, including time, place, execution order, frequency, quantity of operation, and so on.

We made four rules to help the automated restriction identification.

(a) The adverbs having advmod dependency with the operation verb should be included in restriction, which modify the execution of operation. It can be identified by the
dependency `advmod` between the adverbial word(s) and the predicate or a modifier word that it serves to modify. All of the execution time, execution place and execution order of operation can be identified in this way.

(b) The common signs of frequency of operation are `every` period `n`, `n times per period n` and `n times a/an time unit`. For the first two forms, the frequency can be identified from the pattern `every + time unit` or “per”. And for the last one, it can be identified from `nmod:from` the SDP results, which means `temporal modifier`.

(c) The `quantity` of operation means all of the number constraints that should be satisfied during operation execution. For instance, “The SingleUAVFlightPlanScheduler shall only execute one flight plan at a time for each UAV” has a quantity restriction “only one at a time”. And it can be identified by the dependency `nmod:at` between operation and word “time”.

(d) If there is no item in `restriction`, it should be denoted as `∅`.

The algorithm for `restriction` identification is listed in Alg. 6.

```
Algorithm 6: RestrictionIdentification
Input: clause (single requirement entry), pos, dependencies
Output: restriction
restriction = ∅
for all dep ∈ dependencies do
    if dep.type == `advmod` and dep.end ∉ (“when”, “then”)
        /* recognize numbers */
        if dep.end == “only” and ∃ word ∈ clause
            satisfies: (pos(word) == `CD`) then
            restriction = restriction ∪ (“only” + word)
        else
            restriction = restriction ∪ dep.end
    end
    /* Timely modifications should be included in restriction */
    if dep.type == `case` and dep.start == “time” then
        restriction = restriction ∪ (the portion from dep.end to “time” of clause)
    end
end
return restriction
```

4.3. Experimental evaluation on the semantic element identification

In this section we use three open requirement sets which are Unmanned Aerial Systems (UAS) [14], OPENCOSS [3], and WorldVista [2] to evaluate the performance of our semantic element identifying algorithm.

The UAS set including 99 requirements, built by University of Notre Dame, describe the functions of UAV control system based on the template of EARS (Easy Approach to Requirements Syntax) [33].

OPENCOSS, i.e., an Open Platform for Evolutionary Certification Of Safety-critical Systems for the railway, avionics and automotive markets, is an European large scale project dedicated to produce the first European-wide open safety certification platform. This set includes 110 requirements.

The WorldVista set including 117 requirements describes the functions of an electronic health record and health information system.

Just as the discussion in Section 4.2, we need to adjust the requirements firstly to ensure all of them meet the prerequisites about the NL requirements for our automated processing. The adjustment including adding modal verbs, adding conditional adverbial clauses keywords (i.e., “if” and “when”) and replacing pronouns to the corresponding nouns. We would like to calculate the ratio of this kind of requirements requiring adjustments. Thus we scanned all of the requirements in these three datasets, and calculated the number of requirements which are made the specific adjustment, shown in Table 1. According to the table, we can say the ratio of adjusted requirements is small (overall ratio is about 10.74%) and this step is almost effortless.

Our testing set for the semantic element identification includes the all 99 requirements from Unmanned Aerial Systems (UAS) requirement set [14], 30 randomly selected from OpenCoss requirements [3] and 50 randomly selected from WorldVista requirements.

With purposes of evaluation, we need to build the reference answer firstly. Thus, we labeled the semantic elements for the all 179 requirements (i.e., 99 of UAS requirements, 30 of OpenCoss and 50 of WorldVista) manually. Particularly, this manual annotation includes two rounds. In the first round, the first two authors annotated the all 179 requirements independently. They analyzed each requirement and labeled their semantic tuples. Then in the second round, they checked and discussed their annotations face-to-face and made an agreement on the results one by one. This manual annotation occurs before running our algorithm. This process is not affected by the automated results, because we froze and mustn’t modify the reference answer after our algorithm running.

For measurement, we select the metrics of overall accuracy, the accuracy of each tuple and the average accuracy. The overall accuracy refers to the proportion of requirements whose every semantic element is correctly identified. And the accuracy of each tuple refers to the proportion of requirements whose specific tuple is correctly identified, in all requirements. And finally we calculate the average accuracy on all tuples of all requirements. The result is shown in Table 2.

From Table 2, we can make the following observations:

- The overall accuracy of the three datasets is between
Table 1: The number of manual-adjusted requirements in each requirement set

| Req. set | #Req. | #Adding modal verbs (Proportion(%)) | #Adding conditional adverbial clauses keywords (Proportion(%)) | #Replacing pronouns (Proportion(%)) | Overall (Proportion(%)) |
|----------|-------|------------------------------------|---------------------------------------------------------------|------------------------------------|------------------------|
| UAV      | 99    | 4 (4.04)                           | 3 (3.03)                                                      | 14 (14.14)                        | 17 (17.17)             |
| OpenCoss | 110   | 1 (0.91)                           | 2 (1.82)                                                      | 2 (1.82)                           | 5 (4.55)               |
| WorldVista | 117  | 1 (0.85)                           | 8 (6.78)                                                      | 4 (3.39)                           | 13 (11.02)             |
| Overall  | 326   | 6 (1.84)                           | 13 (3.99)                                                     | 20 (6.13)                          | 35 (10.74)             |

Table 2: Evaluation results of the automated semantic elements identification

|                        | UAV       | OpenCoss   | WorldVista | Average |
|------------------------|-----------|------------|------------|---------|
| Total requirements(#)  | 99        | 30         | 50         | 179     |
| Correct annotated requirements (#) | 86       | 25         | 31         | 142     |
| Overall accuracy(%)    | 86.87     | 83.33      | 62.00      | 79.33   |
| Event                  | 98.99     | 96.97      | 98.00      | 97.97   |
| Agent                  | 100.00    | 100.00     | 100.00     | 100.00  |
| Operation              | 94.95     | 93.33      | 88.00      | 92.09   |
| Input                  | 91.92     | 86.67      | 74.00      | 84.20   |
| Output                 | 96.97     | 100.00     | 90.00      | 95.66   |
| Restriction            | 98.99     | 100.00     | 100.00     | 99.66   |
| Average accuracy of all tuples (%) | 96.97   | 96.16      | 91.67      | 94.93   |

62.0% and 86.87%. And the average of the overall accuracy is 79.33%. The identification on WorldVista is the weakest. The primary reason is that comparing with the other two datasets, most of the requirements in WorldVista represent more complicated sentence structure, like multiple nested clauses, lots of infinitives and enum items.

- The average accuracy of all tuples of the three datasets are between 91.67% and 96.97%. And the average of this metric on the three sets is 94.93%. This means that our algorithm works great on identifying the semantic elements from NL requirements.

- Except input, the average accuracy of other tuples is above 92%, and the accuracy of agent is 100%. The excellent identification of agent is due to the well performance of CoreNLP [32] on identifying the subject of sentences. However, the accuracy of the input identification is lower than other tuples. With further analysis, we found that more than 80% errors of input are caused by the false recognition of modifier in entity although the base is identified correctly. Since our algorithm for conflict detection mainly uses the base of entity, and modifiers only provide some assists (seen in Section 5), the errors of input don’t cause much impact on the subsequent conflict detection, which can be seen in the experiment for evaluating the conflict detection algorithm (in Section 5.4).

5. Phase II: Semantic annotation-based requirements conflict detection

The purpose of this section is to detect the conflicts between the requirements which have been annotated with semantic elements. To achieve this goal, we firstly define the types of requirements conflicts and give their detection rules. Then, our conflict detection algorithm is purposed.

5.1. Definition of the conflicts between software requirements

The conflicts we concern can be referred as 3Is: Inconsistency, Inclusion and Interlock. These three categories can be further divided into seven finer types, which will be introduced in the following sections.

During describing the conflicts definition and their detection rules, three binary semantical relations between the tuples or their finer elements (i.e., string) are evolved: equivalent (“=”), inclusion(“⊃”) and contradiction(“∉”). And the related atomic operators are given in the following Section 5.2.
5.1.1. Requirement Inconsistency

**Definition 5.1.** If two requirements Req₁ and Req₂ cannot be satisfied simultaneously, there is an inconsistency relation between them.

This kind of conflict gets the most common attention in the existing works. Chentouf [13] proposed four incompatible types between requirements focusing on operation and event. Kim et al. [28] proposed activity conflicts and resource conflicts based on the structuring Action (verb) + Object + Resource. Moser et al. [36] aimed to identify three conflict types, including conflicts between functional requirements, conflicts between requirement and requirement constraint, and conflicts between requirement and EBNF grammar. However, Moser’s work didn’t give the specific types of conflicts between requirements.

Based on these work, we propose three conflicting types: operation-inconsistency, restriction-inconsistency and event-inconsistency, which are mutually exclusive.

1. **Operation Inconsistency**
   - If and only if Req₁ and Req₂ meet:
     a. event and agent of Req₁ and those of Req₂ are equivalent;
     b. input of Req₁ contains that of Req₂, or input of Req₂ contains that of Req₁;
     c. output of Req₁ contains that of Req₂, or output of Req₂ contains that of Req₁;
     d. The operation of Req₁ contradicts with that of Req₂.

   It is said that there is an operation-inconsistency relation between Req₁ and Req₂, which is an antisymmetric relation. The formal description is as follows:
   
   \[
   \text{Req Glide}_{\text{Req Glide}} = \text{Req Glide}_{\text{Req Glide}} \land \text{Req Glide}_{\text{agent}} = \text{Req Glide}_{\text{agent}} \land \text{Req Glide}_{\text{operation}} = \text{Req Glide}_{\text{operation}} \land \text{Req Glide}_{\text{restriction}} \land (\text{Req Glide}_{\text{input}} \sqsupset \text{Req Glide}_{\text{input}} \land \text{Req Glide}_{\text{output}} \sqsupset \text{Req Glide}_{\text{output}}) \lor (\text{Req Glide}_{\text{input}} \sqsupset \text{Req Glide}_{\text{input}} \land \text{Req Glide}_{\text{output}} \sqsupset \text{Req Glide}_{\text{output}}) \]

   \[
   \text{operation-inconsistency (Req Glide}_{\text{Req Glide}}, \text{Req Glide}_{\text{Req Glide}}) \]

2. **Restriction Inconsistency**
   - If and only if Req₁ and Req₂ meet:
     a. All of event, agent, and operation of Req₁ are equal with those of Req₂ respectively;
     b. input of Req₁ contains that of Req₂, or input of Req₂ contains that of Req₁;
     c. output of Req₁ contains that of Req₂, or output of Req₂ contains that of Req₁;
     d. restriction of Req₁ contradicts with that of Req₂.

   It is said that there is a restriction-inconsistency relation between Req₁ and Req₂, which is an symmetric relation. The formal description is as follows:
   
   \[
   \text{Req Glide}_{\text{Req Glide}} = \text{Req Glide}_{\text{Req Glide}} \land \text{Req Glide}_{\text{agent}} = \text{Req Glide}_{\text{agent}} \land \text{Req Glide}_{\text{operation}} = \text{Req Glide}_{\text{operation}} \land \text{Req Glide}_{\text{restriction}} \land \text{Req Glide}_{\text{input}} \sqsupset \text{Req Glide}_{\text{input}} \land \text{Req Glide}_{\text{output}} \sqsupset \text{Req Glide}_{\text{output}} \lor (\text{Req Glide}_{\text{input}} \sqsupset \text{Req Glide}_{\text{input}} \land \text{Req Glide}_{\text{output}} \sqsupset \text{Req Glide}_{\text{output}}) \]

   \[
   \text{restriction-inconsistency (Req Glide}_{\text{Req Glide}}, \text{Req Glide}_{\text{Req Glide}}) \]

3. **Event Inconsistency**
   - If and only if Req₁ and Req₂ meet: Once the operation of Req₂ is executed, the event of Req₁ cannot be satisfied, which means that Req₁ would not be triggered. This can be described as: suppose there is a condition γ of the event of Req₁ which satisfies:
     a. The agent of γ is equal with the agent of Req₂, and the operation of γ contradicts with Req₂;
     b. The input and output of γ contain (or are contained by) the corresponding tuple of Req₂.

   It is said that there is an event-inconsistency relation between Req₁ and Req₂, and the formal description is as follows:
   
   \[
   \exists \text{ Condition } \in \text{Req Glide}_{\text{event}}, \text{Condition.agent} = \text{Req Glide}_{\text{agent}} \land \text{Condition.operation} = \text{Req Glide}_{\text{operation}} \land ((\text{Condition.input} \sqsupset \text{Req Glide}_{\text{input}} \land \text{Condition.output} \sqsupset \text{Req Glide}_{\text{output}}) \lor (\text{Condition.input} \supset \text{Req Glide}_{\text{input}} \land \text{Condition.output} \sqsupset \text{Req Glide}_{\text{output}})) \]

   \[
   \text{event-inconsistency (Req Glide}_{\text{Req Glide}}, \text{Req Glide}_{\text{Req Glide}}) \]

5.1.2. Requirement Inclusion

**Definition 5.2.** If some tuples of Req₁ semantically contain the corresponding tuples of Req₂, and the other tuples are semantically equal, then there is an inclusion relation between Req₁ and Req₂.

According to the above definition, Req₂ is essentially a (partial) redundant requirement. It should be removed (sometimes Req₁ needs modification meanwhile) to optimize the requirement set, since inconsistency will occur if Req₂ is changed while Req₁ not. Therefore, we consider inclusion as an conflict category.

In the existing research, Walter et al. [48] defined the type of requirement redundancy and Chentouf [13] focused on one special type of inclusion: duplicated requirement. This duplicated requirements are relatively easy to detect. Besides duplication, we concern the semantically containing relation too. We defined two finer inclusion types: operation-inclusion and event-inclusion, which are mutually exclusive.

1. **Operation Inclusion**
   - If and only if Req₁ and Req₂ meet:
     a. event and agent of Req₁ are equal with those of Req₂ respectively;
     b. All of the operation, input, output and restriction of Req₁ contain the corresponding tuples of Req₂.

   It is said that there is an operation-inclusion relation between Req₁ and Req₂, which is an antisymmetric relation. The formal description is as follows:
   
   \[
   \text{Req Glide}_{\text{Req Glide}} = \text{Req Glide}_{\text{Req Glide}} \land \text{Req Glide}_{\text{agent}} = \text{Req Glide}_{\text{agent}} \land \text{Req Glide}_{\text{operation}} = \text{Req Glide}_{\text{operation}} \land \text{Req Glide}_{\text{restriction}} \land \text{Req Glide}_{\text{input}} \sqsupset \text{Req Glide}_{\text{input}} \land \text{Req Glide}_{\text{output}} \sqsupset \text{Req Glide}_{\text{output}} \lor (\text{Req Glide}_{\text{input}} \sqsupset \text{Req Glide}_{\text{input}} \land \text{Req Glide}_{\text{output}} \sqsupset \text{Req Glide}_{\text{output}}) \]

   \[
   \text{operation-inclusion (Req Glide}_{\text{Req Glide}}, \text{Req Glide}_{\text{Req Glide}}) \]

2. **Event Inclusion**
   - If and only if Req₁ and Req₂ meet:
     a. As long as event of Req₁ is satisfied, event of Req₂ can be satisfied for sure, which means that event of Req₁ contains that of Req₂.

   It is said that there is an event-inclusion relation between Req₁ and Req₂, which is a symmetric relation. The formal description is as follows:
   
   \[
   \text{Req Glide}_{\text{Req Glide}} = \text{Req Glide}_{\text{Req Glide}} \land \text{Req Glide}_{\text{agent}} = \text{Req Glide}_{\text{agent}} \land \text{Req Glide}_{\text{operation}} = \text{Req Glide}_{\text{operation}} \land \text{Req Glide}_{\text{restriction}} \land \text{Req Glide}_{\text{input}} \sqsupset \text{Req Glide}_{\text{input}} \land \text{Req Glide}_{\text{output}} \sqsupset \text{Req Glide}_{\text{output}} \lor (\text{Req Glide}_{\text{input}} \sqsupset \text{Req Glide}_{\text{input}} \land \text{Req Glide}_{\text{output}} \sqsupset \text{Req Glide}_{\text{output}}) \]

   \[
   \text{event-inclusion (Req Glide}_{\text{Req Glide}}, \text{Req Glide}_{\text{Req Glide}}) \]
(b) Each of agent, operation, input, output, and restriction of Req₁ is equal with the corresponding tuple of Req₂ respectively.

It is said that there is an event-inclusion relation between Req₁ and Req₂, which is an antisymmetric relation. The formal description is as follows:
\[
\text{Req₁.event} \supset \text{Req₂.event} \land \text{Req₁.agent} = \text{Req₂.agent} \\
\land \text{Req₁.operation} = \text{Req₂.operation} \land \text{Req₁.input} = \text{Req₂.input} \land \text{Req₁.output} = \text{Req₂.output} \land \text{Req₁.restriction} = \text{Req₂.restriction} \\
\Rightarrow \text{event-inclusion (Req₁, Req₂)}
\]

5.1.3. Requirement Interlock

The interlock relation between requirements are described upon the requirement interlock graph.

Definition 5.3. The requirement interlock graph is a digraph, in which each requirement is a vertex. If two requirements meet certain dependency relation, there is an edge between them.

Definition 5.4. If there is a circuit in the interlock graph, we say there is an interlock relation among the requirements in the circuit.

The circuit indicates the interdependency between several requirements, which will probably cause the instability and unreliability during requirement-oriented development. Therefore, we consider interlock is a category of conflicts.

We define two types of interlock: operation-event-interlock and input-output-interlock.

(1) Operation-Event Interlock

Req₁ and Req₂ has operation-event-dependency relation if as long as the operation of Req₁ is executed, the event of Req₂ must be triggered. And there will be an edge from Req₁ to Req₂ in the interlock graph.

The formal description of the condition of operation-event-dependency is as follows:
\[
\forall \text{Event} \in \text{Req₁.event}, (\text{Req₁.agent} = \text{Event.agent} \land \\
\text{Req₁.operation} \supset \text{Event.operation} \land \text{Event.restriction} = \text{Req₁.restriction} \land \text{Req₁.input} \supset \text{Event.input} \land \\
\text{Req₁.output} \supset \text{Event.output}) \\
\Rightarrow \text{operation-event-dependency (Req₁, Req₂)}
\]

If there are multiple requirements with the operation-event-dependency relation in a circle of the requirement interlock graph, we say that all these requirements have operation-event-interlock relation.

Due to the event of these requirements can be triggered in any circumstances, they will be executed repeatedly and forever. There are likely potential conflicts among these requirements.

(2) Input-Output Interlock

Req₁ and Req₂ has input-output-dependency relation if the output of Req₁ contains the input of Req₂ and there are no event inconsistency between these two requirements. And there is an edge from Req₁ to Req₂ in the interlock graph.

The formal description of the condition of input-output-dependency is as follows:
\[
(\exists \text{Entity₁} \in \text{Req₁.output}, \exists \text{Entity₂} \in \text{Req₂.input}, \text{Entity₁} \supset \text{Entity₂}) \land \sim \text{event-inconsistency (Req₁, Req₂)} \land \\
\sim \text{event-inconsistency (Req₁, Req₂)} \\
\Rightarrow \text{input-output-dependency (Req₁, Req₂)}
\]

If there is a circuit in the graph and all requirements in this circle have input-output-dependency, these requirements are said to have input-output-interlock relation.

During the execution, input of each requirement will change continuously, which may result in the unstable implementation.

5.2. Definition of atomic operators

Three binary atomic operators (i.e., equivalent (“=”), inclusion(“⊂”) and contradiction(“∉”)) are used in the definition of conflicts and their definitions are critical for understanding and detecting the conflicts, undoubtedly.

There are six elements with these three operators, including string, entity, entity set, operation, restriction and event. We introduce these six elements and their detection rules in the three operators in the following sections.

5.2.1. String

According to the BNF definition of requirement in Section 4.1, the most basic representation of the tuples including predicate, modifier and base are in the form of strings. We only consider equivalent relation between strings, which means that two strings are identical in case insensitive or synonyms.

5.2.2. Entity

According to the BNF in Section 4.1, the entity is primarily composed of base and modifier. We take Entity₁ and Entity₂ as an example to describe the definition of the three atomic operators upon entity.

The specific conditions are given below:

(a) Inclusion:

(i) When Entity₁ denotes any kind of entity and Entity₂ denotes some special kind of entity, then there is an inclusion relation from Entity₁ to Entity₂, such as “UAV” ⊃ “UAV in flight”. The formal checking condition can be described as:
\[
\text{Entity₁.base} = \text{Entity₂.base} \land (\forall \text{string₁} \in \text{Entity₁.modifier}, \exists \text{string₂} \in \text{Entity₂.modifier}, \text{string₁} = \text{string₂}) \\
\Rightarrow \text{Entity₁} \supset \text{Entity₂}
\]

(ii) In some cases, Entity₂ denotes an entire entity, while Entity₁ denotes a part of it or a parameter of it, then there is an inclusion relation from Entity₁ to Entity₂, such as “UAV” ⊃ “wings of UAV”. In this study two representations of the part relation are involved: “of” and possessive noun (i.e., adding apostrophe (’s) to a noun).

\[
(\exists \text{string} \in \text{Entity₂.modifier}, \text{string} = “of \text{Entity₁.base}” \lor \text{string} = “\text{Entity₁.base’s}”) \\
\Rightarrow \text{Entity₁} \supset \text{Entity₂}
\]

(b) Equivalent:
(i) If both the base and modifier of Entity$_1$ and Entity$_2$ are equal, there is an equivalent relation between them.

Entity$_1$.base = Entity$_2$.base \land Entity$_1$.modifier \in Entity$_2$.modifier \land Entity$_2$.modifier \in Entity$_1$.modifier
⇒ Entity$_1$ = Entity$_2$

5.2.3. Entity$_set$

Entity$_set$ is a set of entity.

In some cases, Entity$_set_1$ semantically includes all entities of Entity$_set_2$. Then, there is an unidirectional inclusion relation from Entity$_set_1$ to Entity$_set_2$.

In some more particular cases, all of entity of Entity$_set_1$ are semantically equal to those of Entity$_set_2$. Then, there is an equivalent relation between these two entity$_set$.

The specific conditions are given below:

(a) Inclusion: each entity in Entity$_set_2$ is included in an entity in Entity$_set_1$.

∀ entity$_2$ ∈ Entity$_set_2$, ∃ entity$_1$ ∈ Entity$_set_1$, entity$_1$ ⊃ entity$_2$
⇒ Entity$_set_1$ ⊃ Entity$_set_2$

(b) Equivalent: Entity$_set_1$ and Entity$_set_2$ have mutual inclusion relation.

Entity$_set_1$ ⊃ Entity$_set_2$ \land Entity$_set_2$ ⊃ Entity$_set_1$
⇒ Entity$_set_1$ = Entity$_set_2$

5.2.4. Operation

We take Operation$_1$ and Operation$_2$ as the example.

In some cases, Operation$_1$ semantically contains Operation$_2$, that is, the execution of Operation$_1$ also means the execution of Operation$_2$. Then there is an unidirectional inclusion relation from Operation$_1$ to Operation$_2$.

In some more particular cases, Operation$_1$ and Operation$_2$ are exactly the same. Then there is a symmetric equivalent relation between them.

In some other cases, Operation$_1$ and Operation$_2$ are semantically contradictory, that is, they cannot be executed at the same time. Then there is a symmetric contradiction relation between them.

The specific conditions are given below:

(a) Equivalent:

Operation$_1$.operation_mode = Operation$_2$.operation_mode
\land Operation$_1$.predicate = Operation$_2$.predicate
⇒ Operation$_1$ = Operation$_2$
⇒ Operation$_1$ ⊃ Operation$_2$

(b) Inclusion: Operation$_1$ includes Operation$_2$ if the predicate of Operation$_1$ is equal with that of Operation$_2$, and the operation_mode of Operation$_1$ is default (i.e., do) or NOT, and the operation_mode of Operation$_2$ is ABLE.

We make this definition because the mode of ABLE means the operation may or may not be executed, while default or NOT means operation should or not be executed, contains the meaning of ABLE.

Operation$_1$.predicate = Operation$_2$.predicate

\land Operation$_1$.operation_mode = “Not” or \emptyset \land Operation$_2$.operation_mode = “Able”
⇒ Operation$_1$ ⊃ Operation$_2$

(c) Contradiction: Operation$_1$ contradicts with Operation$_2$ if the predicate of Operation$_1$ is equal with that of Operation$_2$, and one operation_mode is default (i.e., do) and the other is NOT.

Operation$_1$.predicate = Operation$_2$.predicate
\land ((Operation$_1$.operation_mode = “Not” \land Operation$_2$.operation_mode = \emptyset) \lor (Operation$_1$.operation_mode = \emptyset \land Operation$_2$.operation_mode = “Not”))
⇒ Operation$_1$ \notin Operation$_2$

5.2.5. Restriction

We take Restriction$_1$ and Restriction$_2$ as an example.

Restriction$_1$ contains Restriction$_2$, which means that Restriction$_1$ is stricter than Restriction$_2$. And when Restriction$_1$ is satisfied, Restriction$_2$ also can be satisfied. Then there is an unidirectional inclusion relation from Restriction$_1$ to Restriction$_2$.

In some more particular cases, Restriction$_1$ and Restriction$_2$ are exactly the same. Then there is a symmetric equivalent relation between them.

The specific conditions are given below:

(a) Inclusion: all of constraints in Restriction$_2$ are also in Restriction$_1$.

∀ string$_2$ ∈ Restriction$_2$, ∃ string$_1$ ∈ Restriction$_1$, string$_1$ = string$_2$
⇒ Restriction$_1$ ⊃ Restriction$_2$

(b) Equivalent: Restriction$_1$ and Restriction$_2$ are exactly the same.

Restriction$_1$ ⊃ Restriction$_2$ \land Restriction$_2$ ⊃ Restriction$_1$
⇒ Restriction$_1$ = Restriction$_2$

5.2.6. Event

We take Event$_1$ and Event$_2$ as an example.

Event$_1$ containing Event$_2$ means when Event$_1$ is satisfied, Event$_2$ must also be satisfied. Then there is an unidirectional inclusion relation from Event$_1$ to Event$_2$.

When Event$_1$ and Event$_2$ are exactly the same, or the corresponding tuples are synonymous, there is a symmetric equivalent relation between them.

If any two conditions of one event are semantically contradictory, then this event cannot be satisfied. We say that there is a symmetric contradiction relation between these two conditions.

The specific conditions are given below:

(a) Inclusion: if for any condition $γ$ in event$_2$, there are at least one conditions in event$_1$ that can contain $γ$, event$_1$ contains event$_2$.

∀ condition$_2$ ∈ event$_2$, ∃ condition$_1$ ∈ event$_1$, condition$_1$.agent = condition$_2$.agent \land condition$_1$.operation ⊃ condition$_2$.operation \land condition$_1$.input ⊃ condition$_2$.input \land condition$_1$.output
Contradiction: if any two conditions of one event conflict with each other, this event is contradictory. 
\[ \exists \text{condition}_1, \text{condition}_2 \in \text{event}, \text{condition}_1, \text{agent} = \text{condition}_2, \text{agent} \wedge \text{condition}_1, \text{input} \supset \text{condition}_2, \text{input} \wedge \text{condition}_1, \text{operation} \nexists \text{condition}_2, \text{operation} \wedge \text{condition}_1, \text{output} \supset \text{condition}_2, \text{output} \equiv \text{event}_1 \supset \text{event}_2 \]

Equivalent: Event_1 and Event_2 are exactly same or the corresponding tuples are synonymous, there are equivalent relation between them. 
\[ \text{event}_1 \supset \text{event}_2 \wedge \text{event}_1 \supset \text{event}_2 \Rightarrow \text{event}_1 = \text{event}_2 \]

5.3 Software requirements conflict detecting algorithm

Before conducting the algorithm of conflict detection based on their definitions, we design four steps for the preprocessing.

(1) Object clause is often a grammar-complete sentence. For the sake of conflict identification, we parse object clause into eight-tuple too. The object clause can be automatically identified by ccomp dependency. NOTE: ccomp from the SDP, means clause complement.

(2) Detect contradiction relation of the multiple events of one single requirement, namely self-contradictory event.

(3) Split the requirement statements. If one requirement has multiple event clauses with “or” relation, combine each clause and the main clause into new requirements. Remove the original requirements from the requirement set.

(4) Put the requirements that have the same event and agent into a group. Then we can identify the conflicts between requirements according to their groups. Some conflicts can only occur within a group such as operation-include, operation-inconsistency and restriction-inconsistency. And event-include and event-inconsistency happen in the requirements in different groups. Requirements grouping is dedicated to improve the efficiency of the conflict detection.

Then we detect the conflicts according to the definitions in Section 5.1. The detection algorithm is listed in Alg. 2.

Now we analyze the time complexity of the conflict detection algorithm. Let the number of requirements in the input requirement set R is n, we traverse all the requirements in the first 14 lines, obviously, the time complexity is O(n).

And after this, let the number of requirements in R is n, therefore, the number of all pairs of requirements is n^2. Then we traverse all the pairs by the same group (line 15 - 19), by not the same group (line 20 - 27), and the whole (line 28 - 32). Therefore, the time complexity is O(n^2).

In the end, we find all the circuits from the graph with n vertexes. Let the number of edges is e, the time complexity is O(ne).

In summary, the overall time complexity of the algorithm is O(n_0 + n^2 + ne). In the case where n is closer to n_0, the time complexity is O(n^2 + ne). Considering that there are few conflicts

**Algorithm 7: Conflict Detection Algorithm**

**Input:** A requirement set R with semantically annotated requirements r_1, r_2, ..., r_n

**Output:** The conflict set C

/* Preparing for conflicts detection */

for all requirement r E R do

if there is an object clause in r then

Replace r with object clause in R.

end

if event e of r is self-contradictory, namely conflict(e, e) then

Add (r, r) to C.

Remove r from R.

end

if event e of r \neq \text{ALL} and e is consisted of multiple parts with “or” relation then

Combine each part of e and the remaining part of r into new requirements r'_1, r'_2, ..., r'.

Add r'_1, r'_2, ..., r' to R.

Remove r from R.

end

end

/* Detect the conflicts between the requirements in the same group */

for all pairs of requirements in the same group (r_1, r_2) in R^2 do

if operation-inconsistency(r_1, r_2) or restriction-inconsistency(r_1, r_2) then

Add (r_1, r_2) to C.

end

end

/* Detect other conflicts, and build interlock graphs */

for all pairs of requirements not in the same group (r_1, r_2) in R^2 do

if operation-inconsistency(r_1, r_2) then

Add (r_1, r_2) to C.

end

end

/* Detect requirement interlocks */

for all circuit in operation-event-interlock-graph or input-output-interlock-graph do

Add all requirements in circuit (r_1, r_2, ..., r_n) to C.

end

return C.
in the requirements, therefore, $e$ is not much bigger than $n$. The overall complexity is the square of the number of requirement.

5.4. Experimental evaluation on the conflict detection

To evaluate the performance of automated conflict detection, we used UAV and WorldVista requirement sets in Section 4.3. Different from that in the experiment of Section 4.3, we used the full sets, that is, 99 requirements in UAV set and 117 in WorldVista set. However, the conflicts among them are unknown in advance.

Therefore, we also selected the requirement sets of two more real projects whose conflicts can be collected meanwhile. The first set is the requirements of a telecom management system from work [13] and all of the conflicting requirements as well as the conflict types are given.

The second set includes the requirements of a Solar power supply system built by California ISO company since there are several versions of the requirement specifications online and the modified content are clearly annotated in the newer version. These modifications are good source of conflicts among requirements cross versions. For instance, one requirement is “Market system shall calculate the total EIM Transfer Limits for both the import and export directions” in the old version, and is modified into “Market system shall calculate and broadcast the total EIM Transfer Limits for both the import and export directions” in the new version. Therefore, there is Operation Inconsistency between these two requirements cross two versions. We selected 26 NL requirements from the latest three versions. The other ones are with restricted NL (e.g., use case), not the target of this study. We found 12 conflicting requirements with 7 conflicts, 5 Input-Output Interlock, one Restriction Inconsistency and one Operation Inclusion.

For the UAV and WorldVista sets, we manually checked each of the detected results, judged and recorded their correctness or not. Accordingly, we calculated the precision. Recall was not computed because we don’t have the full sets of conflicts. While, for Telecom and Solar we work out both the precision and recall by comparing the automated detection with the golden standard. The result is shown in Table 3. In this table, we list the total number of requirements in the four datasets, the number of conflicts (if known), the number of detected conflicts, number of the correct detection, as well as the precision and recall values. Besides, we give the overall calculation of each metric.

Overall, our algorithm yields great performance of precision and recall on the two datasets. For the requirement sets with unknown conflicts (i.e., UAV and WorldVista), the precision is between 78% and 79%. And for the other two sets with known conflicts (i.e., Telecom Management and Solar Power Supply), the precision is above 87%, especially for Solar the precision reaches 100%. And the detection recall on both these two datasets reaches 100%.

For the sake of clearly evaluating the performance of our algorithm on the conflict type detection, we further analyzed the number of each type of conflicts detected by our algorithm in the sets of UAV and WorldVista, and the results are shown in Table 4. We found that for the two requirement sets with unknown conflicts, the detected conflicts are mainly input-output-interlock. There are 13 and 17 input-output-interlock conflicts in UAV and WorldVista, accounting for 92.86% and 89.47% respectively. While the number of correct identification is 10 and 13, the precision is 76.92% and 76.47%. The reason why there are so many input-output-interlock conflicts is that some nouns or noun phrases appear largely in the requirement set. For instance, the word “flight plan” appears 21 times, in which 18 times are input and 12 times are output (Note that the input and output may be overlapped). Therefore, lots of requirements are interdependent caused by the same input or output, meaning that their input and output contain a number of same entities. As for the false conflicts, one possible reason is that some entities in input or output are recognized incorrectly. Another reason is not all input-output-interlock relationships are real conflicts, some of which are potential risk of inconsistence.

In addition to input-output-interlock relation, other conflict types detected are only restriction-inconsistency and operation-inclusion, whose identification are all correct. We think the reason is that requirement inconsistency types are stricter than requirement inclusion and interlock. While these requirement sets must have been improved several times during the engineering practical and therefore have high qualities, so there is no such conflict in these sets.

For requirement sets with known conflicts, the detected conflicts contain all types of conflicts we defined and are comprehensive. All 14 known conflicts can be detected, indicating that the our conflict detection rules are well designed and can handle the requirement documents in these two different fields. And there is only one false positive conflict, which is input-output-interlock, for one entity in input is recognized incorrectly. If we correct the entity, the false detection can be avoided. This shows that our conflict detection rules work.

Based on the evaluation on the two kinds of requirement sets, we get the overall measurements by calculating the overall conflict numbers (including the total conflicts, known conflicts, detected conflicts and the correct identified number) and the metrics including the precision (i.e., $\frac{\text{Overall correctly identified}}{\text{Overall detected conflicts}}$) and recall (i.e., $\frac{\text{Overall correctly identified}}{\text{Overall known conflicts}}$). For the two requirement sets from academic groups, the overall precision is about 78.79%. And for the other two sets, the overall precision reached 93.33%, and the total recall rate reached 100.00%, indicating that it can accurately detect conflicts in the requirement set.

6. Threats to validity

Threats to validity are discussed from internal, external and construct validity.

Internal validity is about how well the experiment is done so that a causal relationship can be concluded from the study. The biggest threat to internal validity is from manual labeling, which may bring in subjective uncertainty. To mitigate...
this threat, the labeling is performed by two authors with two rounds. Firstly, the first author did the labeling carefully. Then, the second author joined in and worked with the firstly author to jointly review each of the labeling results, discussed the divergent opinions until agreements were reached on all labels.

External validity is about the generalizability of our approach. Our approach includes two parts which are semantic elements identification and conflict detection. We used the requirements of five systems from different domains created by different groups on the evaluation. To be specific, three sets were employed for the first part, and four for the second one. Therefore, we mitigate bias to any particular requirement set. Another possible threat to generalizability is the types of conflicts. We collected the seven types mainly from academic researches and our project experience. However, these can be extended with regards of more domain background and project knowledge. In the future, we plan to work on more conflict types.

Construct validity discusses the extent to which the goal that is designed to measure is accurately measured. For conflict detection, we only calculated precision for the two requirement sets of UAV and WorldVista because obtaining the full sets of conflicts requires sound domain knowledge and it is hard to make sure that. So we prepared two more requirement sets Telecom Management and Solar Power Supply whose conflict sets are known beforehand. In the end, we can measure both the recall and precision of our approach for better evaluation.

7. Conclusion and the future work

Requirements conflict is highly likely delaying the progress of software development, and is also one important cause of software instability and imperfect functions. Most of the previous conflict detection approaches requires (semi-)formal formats of the requirements. However, natural language requirements is the major representation in industry. Thus, we proposed an approach FSARC to automatically detect the conflicts between natural language requirements, which analyzes the finer semantic elements in NL requirements, and then detects the conflicts beyond the semantic model of these requirements. We designed two experiments for evaluating the semantic annotations and conflicts detection respectively involving five open requirements sets. Evaluation results show that our approach is well-behaved. To be specific, for semantic annotation, with a total 179 requirements from three requirement sets, the total accuracy of automatic annotation reached 79.33%. And for conflict detection, with a total of 242 requirements from four requirement sets, the total recall of the algorithm reached 100.00%, and the precision reached 83.33%.

In future, we plan to combine the domain model and general dictionary for obtaining more accurate relationships between the phrases to improve the performance of our approach on both semantic annotation and conflict detection. Besides, we plan to conduct a systematic review on project experts who have deep domain knowledge and at least a few years project experience, with the expectation of obtaining more conflict types as well as their usual detection methods in practice, for improving our approach.

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