Formalisation of the Integration of Behavior Trees

Kushal Ahmed, M. A. Hakim Newton, Lian Wen, Abdul Sattar
Institute for Integrated and Intelligent Systems
Griffith University, Nathan, QLD 4111, Australia
{k.ahmed, hakim.newton, l.wen, a.sattar}@griffith.edu.au

ABSTRACT

In this paper, we present a formal definition of the integration of the requirements modeling language Behavior Trees (BTs). We first provide the semantic integration of two interrelated BTs using an extended version of Communicating Sequential Processes. We then use a Semantic Network Model to capture a set of interrelated BTs, and develop algorithm to integrate them all into one BT. This formalisation facilitates developing (semi-)automated tools for modeling the requirements of large-scale software intensive systems.

Categories and Subject Descriptors

D.2.1 [Software Engineering]: Requirements/Specifications—*requirements modeling, process automation*

Keywords

Behavior Trees; Behavior Engineering; Integration; Merge; CSP; Semantic Network Model

1. INTRODUCTION

Requirements Engineering (RE) often starts with a set of scattered and unstructured system requirements with a view to achieving an integrated and structured formal specification. Unsurprisingly, such requirements may be filled with problems, such as ambiguity, inconsistency, redundancy, and incompleteness. As a result, the process of transforming the requirements into a formal specification is extremely complicated. The transformation process must therefore be able to identify issues in the requirements in a way easy to understand, and the model must be structured such that it can be cross referenced with the original requirements document.

Behavior Engineering (BE) was developed to address this problem [5, 15]. It uses Behavior Tree (BT) as the graphical notation. A BT contains a range of constructs that cover state-based manipulations, as well as more abstract concepts such as synchronisation and message passing, along with

typical concurrency, choice and iteration control structures familiar to specification and programming languages.

Each requirement is translated into one or more BTs, and each node in the tree is tagged with the requirements identifier allowing traceability back to the original informal requirements. BTs may have syntactically matching constructs. Therefore, they may then be progressively integrated into one holistic model of the system, which serves as a formal specification. This process may reveal inconsistencies, redundancies, incompleteness, and ambiguities. BTs have been adopted for industrial use, in particular Raytheon Australia [1], who invested resources to developing a BT editor [10]. There are many other tools on BTs [14, 18, 20, 23], some of them support validation and verification as well.

However, the integration of the BTs is still informal, ad-hoc and manual. Colvin and Hayes [4] provided the semantics of a BT using Hoare's process algebra Communicating Sequential Processes (CSP) [9, 19] as its base, which is a well established and elegant formal notation for describing interactions between concurrent processes. By extending it, they defined CSP_{σ} to include state-based constructs such as tests and updates, and message passing facility similar to publish/subscribe models of the communication [6]. In this paper, we first provide the semantic integration of two interrelated BTs using an extended version of CSP_{σ} . We then use a Semantic Network Model (SNM) [3] to capture a set of interrelated BTs, and develop algorithm to integrate them all into one BT. This formalisation facilitates developing (semi-)automated tools for modeling the requirements of large-scale software intensive systems.

Paper organisation: Section 2 briefly describes BTs and their interrelations, CSP_{σ} and SNM; Section 3 formalises the integration of two interrelated BTs; Section 4 extends the formalism for a set of BTs; Section 5 explores related literature; and finally Section 6 presents our conclusion.

2. BACKGROUND

In this section, we briefly describe the constructs of BTs and their interrelations, CSP_{σ} and SNM.

BTs and their interrelations: Fig. 1(a) shows a BT of a requirement (ID: R2) of a Security Alarm System (SAS) [3, 17]. It mentions the initialisation scenarios for activating the SAS. Fig. 1(b) displays the contents of a BT node. Each node is associated with a component having a behavior. The type of behavior may be internal input ($><$), external input ($>><$), internal output ($<>$), external output ($<<>$), event (????), selection, (??), or state realisation ([]) etc.

Figure 1: Behavior Tree and Attributes of a node

The node operators such as reversion ($\wedge$), reference ($=>$), branch kill ($--$) and synchronisation ($=$) are used to indicate control flow beyond simple sequential execution and branching. The nodes can be connected in different ways such as sequential, parallel, atomic and alternative ([4, 5]).

Notice BT2 in Fig. 1 (a) and BT3 (ID: R3) in Fig. 2(a). BT2's ending scenario activating the SAS is the starting scenario of BT3. This means, BT2 and BT3 are interrelated, and can be integrated into one BT (Fig. 3(a)).

Figure 2: Relation in BTs (dots: nodes skipped)

Figure 3: BT2-3, BT5 and BT6

We use a very generic representation of *Behavioral Model* (BM), denoted by m , to refer to the mathematical representation of a BT [2]. As such, a BT node is referred to as *Behavioral Unit* (BU), denoted by u . A BU consists of a set of *attributes* $\{a_k\}$ and so does an edge between two BUs. Each attribute a_k has a *name*, denoted by $name(a_k)$, and a *value*, denoted by $value(a_k)$. We use $parents(u)$ and $childs(u)$ to denote the set of parent and child BUs.

We say a *parent* BM m_p forms an *integration relation* with a *child* BM m_c , denoted by $R(m_p, m_c)$, if a BU u_p in m_p is *equivalent* to the root BU u_c of m_c [3, Section-2]. As such, BT5 and BT6 form an integration relation because u_2 of BT5 and u_0 of BT6 are equivalent (Fig. 3(b, c)). We use $R^k(m_p, m_c)$ to denote k -th relation between m_p and m_c . We consider three types of integration relation: *root-root*, *branch-root* and *leaf-root* relations [2].

CSP $_{\sigma}$: It is an extension of the process algebra CSP. It allows concurrent processes to communicate synchronously

via shared events, and to manipulate and check the value of state variables [4]. A BT is transformed into a CSP $_{\sigma}$ process, and each node is transformed into a CSP $_{\sigma}$ action. Different operators control the concurrency in the processes.

SNM: An SNM captures the BMs and their interrelations into an annotated graph, which stores their meta-level information such as their acceptability states (Included (IN), Excluded (EX) and Undecided (UN)), the confidences of the BMs to be Included in the specification and the similarity measure of the parent and child BUs for a relation etc [3].

3. FORMAL INTEGRATION

In this section, we first provide the semantics of a BM. We then formalise the integration of two interrelated BMs.

3.1 Semantics of a BM: Extension of CSP $_{\sigma}$

A BM consists of BUs connected by edges. The attributes of each of these entities may have operational semantics. For example, the *behavior-type* attribute of a BU indicates the type of action such as state realisation, selection, guard, input or output for the component denoted by *component-name*. The *node-operator* attribute indicates recursion, interrupt, restart or synchronisation. Thus, a BU represents a CSP $_{\sigma}$ action characterised by the attributes of the BU. The *type-name* attribute of an edge indicates atomic, sequential, parallel or alternative step from one action to another. An edge may have timing constraints. Thus, an edge represents the characteristics of the step between actions such as actions performed non-interleaving (atomic), sequential, parallel or external choice (alternative), which may further be executed after a fixed amount of time delay. CSP $_{\sigma}$ [4] does not consider the edge as an entity, however it provides semantics of atomic, sequential, parallel and alternative steps.

Fig. 4 shows a sample BM having BUs connected with edges. CSP $_{\sigma}$ defines semantics of the BM considering the attributes (e.g. *behavior-type*) of the BUs and the type of edges. It also defines non-sequential execution of the processes for *node-operator* attribute. On top of it, we can extend the CSP $_{\sigma}$ as follows.

Figure 4: Sample BM with BUs connected with edges

Let P_{u_i} denotes the CSP $_{\sigma}$ process starting from the CSP $_{\sigma}$ action characterised by the BU u_i . As such, P_{u_0} denotes the CSP $_{\sigma}$ of the BM shown in Fig. 4. Here, the root BU u_0 has three children u_1 , u_2 and u_3 connected by $e_{0,1}$, $e_{0,2}$ and $e_{0,3}$ respectively. If the CSP $_{\sigma}$ action for u_0 is performed, the CSP $_{\sigma}$ process P_{u_0} may behave as P_{u_1} , P_{u_2} and/or P_{u_3} after following the steps characterised by the edges $e_{0,1}$, $e_{0,2}$ and $e_{0,3}$ respectively. Therefore, P_{u_0} can be written by the following way:

$$P_{u_0} ::= \parallel_{u_j} ((u_0, e_{0,j}) \rightarrow P_{u_j}) \text{ s.t. } u_j \in \text{childs}(u_0) \quad (1)$$

Symbol $\parallel_{u_j}$ indicates concurrent processes for each u_j .

DEFINITION 1 (SEMANTICS OF A BM). *The semantics of a BM is a CSP $_{\sigma}$ with BUs as the CSP $_{\sigma}$ actions and edges as the steps from one action to another. Let P_{u_i} denotes the CSP $_{\sigma}$ process starting from the action characterised by the BU u_i , which has children BUs denoted by $\text{childs}(u_i)$, then,*

$$P_{u_i} ::= \parallel_{u_j} ((u_i, e_{i,j}) \rightarrow P_{u_j}) \text{ where } u_j \in \text{childs}(u_i) \quad (2)$$

3.2 Integrating BMs: Merging CSP_σ processes

If two BMs have *root-root*, *branch-root* or *leaf-root* relation, they can be integrated into one BM by merging their equivalent BUS pair into one BU. By Definition 1, a BM represents a CSP_σ process and each BU represents a CSP_σ action. As a result, integrating two BMs means merging two CSP_σ processes. This further implies that the CSP_σ actions represented by the equivalent BUSs can be merged into one CSP_σ action. In that case, the attributes that characterise the merged CSP_σ action would depend on the merging of the attributes of the equivalent BUSs. We refer to the merged CSP_σ action as the *least common action* (lca).

DEFINITION 2 (LEAST COMMON ACTION). *If two BMs have an integration relation, the CSP_σ actions represented by the equivalent BUSs u_p and u_c can be merged into one CSP_σ action, referred to as the least common action (lca) of the two CSP_σ processes represented by the BMs respectively.*

In addition, the equivalent BUSs may have child BUSs which themselves may again be equivalent and so on. That means, the CSP_σ actions for the child equivalent BUSs can again be merged into one CSP_σ action (Procedure 4); which may continue till a leaf BUS is reached. Thus a *refinement* of CSP_σ processes must follow after the lca to achieve a merged CSP_σ process that is more defined than the original two CSP_σ processes. In this section, we first illustrate the integration and then formalise it using the extended version of CSP_σ.

3.2.1 Illustration of the Integration

The BUS u_2 in BT5 (Fig. 3(b)) is equivalent to the root BUS u_0 in BT6 (Fig. 3(c)). Therefore, they form an integration relation (Fig. 5(a)). So they can be integrated into one BT. The integration starts from integrating the BUSs u_2 and u_0 (Fig. 5(b)). Note that the *behavior type* of these two BUSs are different: *state realisation* and *event*. Here, *state realisation* has high precedence over *event*. So the integrated BUS takes *state realisation* value of the *behavior type* attribute. After integrating these BUSs, the child BUSs u_3 (of BT5) and u_1 (of BT6) of these former BUSs are equivalent again (Fig. 5(b)).

Therefore, the edges $e_{2,3}$ of BT5 and $e_{0,1}$ of BT6 are integrated first and then the BUSs u_3 of BT5 and u_1 of BT6 are integrated. Now, the child BUSs u_4 (of BT5) and u_2 (of BT6) further are equivalent (Fig. 5(c)). The integration ends after integrating the edges $e_{3,4}$ of BT5 and $e_{1,2}$ of BT6, and the BUSs u_4 of BT5 and u_2 of BT6 (Fig. 5(d)). Thus, the integration starts by integrating the equivalent BUSs which cause the integration relation to be formed between the BMs. Then, the integrated BM goes through further refinement by integrating the equivalent child BUSs and so on.

3.2.2 Integration for root-root relation

Let, u_p and u_c represent the root BUSs of the BMs having *root-root* relation. From Definition 1,

$$P_{u_p} ::= \|_{u_i} ((u_p, e_{p,i}) \rightarrow P_{u_i}) \text{ where } u_i \in \text{childs}(u_p) \quad (3)$$

$$P_{u_c} ::= \|_{u_j} ((u_c, e_{c,j}) \rightarrow P_{u_j}) \text{ where } u_j \in \text{childs}(u_c) \quad (4)$$

Let, $u_i = u_p$, $u_j = u_c$ as shown in Fig. 6. Suppose $u_i \oplus u_j (= u_{ij})$ denotes their integration. Assume the child BUSs u'_i and u'_j are again equivalent. Therefore, we have to integrate the edges $(e_{i,i'} \oplus e_{j,j'} = e_{ij,i'})$, and the BUSs $(u'_i \oplus u'_j = u'_{ij})$ as indicated by the dotted boxes in Fig. 6. Now,

$$P_{u_i} ::= (u_i, e_{i,i'}) \rightarrow P_{u'_i} \|_{u_k} ((u_i, e_{i,k}) \rightarrow P_{u_k}) \quad (5)$$

where $u_k \in \{\text{childs}(u_i) - u'_i\}$

Figure 5: Step-by-step integration of BT5 & BT6

$$P_{u_j} ::= (u_j, e_{j,j'}) \rightarrow P_{u'_j} \|_{u_k} ((u_j, e_{j,k}) \rightarrow P_{u_k}) \quad (6)$$

where $u_k \in \{\text{childs}(u_j) - u'_j\}$

Figure 6: Sample BMs having root-root relations

Let $P_{u_i} \oplus P_{u_j} ::= P_{u_{ij}}$ denotes the merging. Therefore,

$$P_{u_{ij}} ::= \|_{u'_k} ((u_{ij}, e_{ij,i'j'}, u'_{ij}) \rightarrow P_{u'_k}) \rightarrow P_{u'_k} \|_{u_k} ((u_{ij}, e_{ij,k}) \rightarrow P_{u_k}) \quad (7)$$

where $u'_k \in \{\text{childs}(u'_i) \cup \text{childs}(u'_j)\}$ and

$$u_k \in \{(\text{childs}(u_i) \cup \text{childs}(u_j)) - \{u'_i, u'_j\}\}$$

PROCEDURE 1 (INTEGRATING root-root RELATED BMS). *If two BMs have root-root relation, the CSP_σ processes P_{u_p} and P_{u_c} represented by the BMs can be merged into one CSP_σ process, denoted by $P_{u_{pc}} ::= P_{u_p} \oplus P_{u_c}$, in two phases:*

- 1) *Least Common Action: The merging begins with producing the lca of the two processes. Thus,*

$$P_{u_p} \oplus P_{u_c} ::= \|_{u_k} (((u_p \oplus u_c), e_{pc,k}) \rightarrow P_{u_k}) \quad (8)$$

where $u_k \in \{\text{childs}(u_p) \cup \text{childs}(u_c)\}$

- 2) *Refinement: Let, $u_i = u_p$, $u_j = u_c$ and so $u_{ij} = u_{pc}$. For each equivalent BUSs pairs u'_i and u'_j such that $u'_i \in \text{childs}(u_i)$ and $u'_j \in \text{childs}(u_j)$, the refinement steps are:*

- (a) *Let, we rewrite the CSP_σ process $P_{u_{pc}}$ as $P_{u_{pc}} ::= P_{u_{pc}} \leadsto P_{u_{ij}}$ denoting $P_{u_{pc}}$ contains a CSP_σ process $P_{u_{ij}}$ at a certain point in time along with other concurrent processes. Here,*

$$P_{u_{ij}} ::= \|_{u'_k} (((u_i \oplus u_j), (e_{i,i'} \oplus e_{j,j'}), (u'_i \oplus u'_j)), e_{i'j',k'}) \rightarrow P_{u'_k} \|_{u_k} ((u_{ij}, e_{ij,k}) \rightarrow P_{u_k}) \quad (9)$$

where $u'_k \in \{\text{childs}(u'_i) \cup \text{childs}(u'_j)\}$ and

$$u_k \in \{(\text{childs}(u_i) \cup \text{childs}(u_j)) - \{u'_i, u'_j\}\}$$

- (b) *Assign $u_i = u'_i$ and $u_j = u'_j$, and perform Refinement.*

3.2.3 Integration for branch-root relation

Let, u_p and u_c represent the equivalent BUs of the BMs having *branch-root* relation. Suppose, u_r denotes the root of the parent BM. Let, we rewrite the CSP_σ process P_{u_r} as $P_{u_r} ::= P_{u_r} \rightsquigarrow P_{u_p}$. Let, $u_i = u_p$, $u_j = u_c$ as shown in Fig. 7. The equivalent BUs and corresponding edges have to be integrated as indicated by the dotted boxes in Fig. 7. $P_{u_{ij}}$ of P_{u_i} and P_{u_j} can be formed similarly by Equation 7.

Figure 7: Sample BMs having branch-root relations

PROCEDURE 2 (INTEGRATING branch-root RELATED BMs).

If two BMs have branch-root relation, the CSP_σ processes P_{u_r} and P_{u_c} represented by the BMs can be merged into one CSP_σ process, denoted by $P_{u_r} ::= P_{u_r} \oplus P_{u_c}$, in two phases:

1) *Least Common Action*: The merging begins with producing the lca of the two processes P_{u_p} and P_{u_c} . Thus,

$$P_{u_{pc}} ::= P_{u_r} \rightsquigarrow P_{u_{pc}} \text{ where} \\ P_{u_{pc}} ::= \parallel_{u_k} (((u_p \oplus u_c), e_{pc,k}) \longrightarrow P_{u_k}) \quad (10) \\ \text{where } u_k \in \{\text{childs}(u_p) \cup \text{childs}(u_c)\}$$

2) *Refinement*: Let, $u_i = u_p$, $u_j = u_c$ and so $u_{ij} = u_{pc}$. For each equivalent BUs pairs u'_i and u'_j such that $u'_i \in \text{childs}(u_i)$ and $u'_j \in \text{childs}(u_j)$, the refinement steps are:

(a) Let, we rewrite P_{u_r} as $P_{u_r} ::= P_{u_r} \rightsquigarrow P_{u_{ij}}$. Here,

$$P_{u_{ij}} ::= \parallel_{u'_k} (((u_i \oplus u_j), (e_{i,i'} \oplus e_{j,j'}), (u'_i \oplus u'_j)), \\ e_{i'j',k'}) \longrightarrow P_{u'_k} \parallel_{u_k} ((u_{ij}, e_{ij,k}) \longrightarrow P_{u_k}) \quad (11) \\ \text{where } u'_k \in \{\text{childs}(u'_i) \cup \text{childs}(u'_j)\} \\ \text{and } u_k \in \{(\text{childs}(u_i) \cup \text{childs}(u_j)) - \{u'_i, u'_j\}\}$$

(b) Assign $u_i = u'_i$ and $u_j = u'_j$, and perform Refinement.

3.2.4 Integration for leaf-root relation

Let, u_p and u_c represent the equivalent BUs of the BMs having *leaf-root* relation. Suppose, u_r denotes the root of the parent BM. Since it is a *leaf-root* relation, there exists no child of the leaf BU. Let, we rewrite the CSP_σ process P_{u_r} as $P_{u_r} ::= P_{u_r} \rightsquigarrow P_{u_p}$. Fig. 8 shows that the merging is performed by integrating the equivalent BUs u_p and u_c .

Figure 8: Sample BMs having leaf-root relations

PROCEDURE 3 (INTEGRATING leaf-root RELATED BMs).

If two BMs have leaf-root relation, the corresponding processes P_{u_r} and P_{u_c} can be merged into one CSP_σ process, denoted by $P_{u_r} ::= P_{u_r} \oplus P_{u_c}$, by producing the lca:

$$P_{u_r} ::= P_{u_r} \rightsquigarrow P_{u_{pc}} \text{ where} \\ P_{u_{pc}} ::= \parallel_{u_k} (((u_p \oplus u_c), e_{pc,k}) \longrightarrow P_{u_k}) \quad (12) \\ \text{where } u_k \in \text{childs}(u_c)$$

3.3 Integrating BUs: Merging CSP_σ Actions

If two BUs are equivalent, the integration of them represents a merged CSP_σ action. It is characterised by the attributes of the integrated BU, which we get by integrating the attributes of the given BUs. The integration of two attributes a_i and a_j , given their names are same, is denoted by $a_i \oplus a_j$; which is formalised in Section 3.4. The names of the attributes may not be syntactically same, but may have same mapping. We assume that names of the attributes are syntactically same if they have the same mapping.

PROCEDURE 4 (INTEGRATING BUs: $u_p \oplus u_c$). If the BUs u_p and u_c are equivalent, the corresponding CSP_σ actions can be merged into one CSP_σ action that is characterised by the attributes of the BU $u_{pc} = u_p \oplus u_c$ formed by integrating the attributes of u_p and u_c by the following rules:

- 1) If there exists a pair of attributes $a_i \in u_p$ and $a_j \in u_c$ such that $\text{name}(a_i) = \text{name}(a_j)$, then an attribute $a_k \in u_{pc}$ is formed such that $a_k = a_i \oplus a_j$.
- 2) If there exists an attribute $a_i \in u_p$ such that $\text{name}(a_i) \neq \text{name}(a_j)$ for all attribute $a_j \in u_c$, then an attribute $a_k \in u_{pc}$ is formed such that $a_k = a_i$.
- 3) If there exists an attribute $a_j \in u_c$ such that $\text{name}(a_j) \neq \text{name}(a_i)$ for all attribute $a_i \in u_p$, then an attribute $a_k \in u_{pc}$ is formed such that $a_k = a_j$.

Due to similarity we omit the formalisation of integrating edges i.e. merging the steps between the CSP_σ actions.

3.4 Integrating attributes

When integrating two BUs or edges, we essentially integrate the attributes of these entities. If the names of the attributes a_i and a_j are same, we form an integrated attribute $a_k = a_i \oplus a_j$. The value of the integrated attribute a_k depends on the values of the attributes a_i and a_j . If the values are same, then the integrated value is also the same. Otherwise, the value of the integrated attribute is formed by many different operations between the original values.

PROCEDURE 5 (INTEGRATING ATTRIBUTES: $a_i \oplus a_j$). If two attributes a_i and a_j , given that $\text{name}(a_i) = \text{name}(a_j)$, are integrated into one attribute a_k where $\text{name}(a_k) = \text{name}(a_i)$, then $\text{value}(a_k)$ is formed by the following rules:

- 1) If $\text{value}(a_i) = \text{value}(a_j)$, then $\text{value}(a_k) = \text{value}(a_i)$.
- 2) Otherwise, $\text{value}(a_k) = \text{value}(a_i) \oplus \text{value}(a_j)$.

The integration of the values i.e. $\text{value}(a_i) \oplus \text{value}(a_j)$ can be performed in many different ways.

Choice: The value of the integrated attribute may be selected from the values of the original values. For example, the values of the *behavior type* attribute may be different. One may have *state realisation* ([]) and other may have *selection* (??) as values. In this case, the value of the integrated attribute would be *state realisation*. In this case, we say that the property of the attribute *behavior type* is *choice*.

If the property of an attribute is *choice*, the values of that attribute are kept into a sorted set from high to low precedence order. For example, *state realisation* has a high precedence over *selection* for the *behavior type* attribute.

Combination: The value of the integrated attribute may be the combination of the original values. For example, the value of *traceability link* attribute may be different. The values may be R2 and R3. In this case, the value of the integrated attribute would be the combination of those values i.e. {R5, R6}. We say that the property of the attribute *traceability link* is *combination*.

Mapping: The values of the attributes may be syntactically different, but semantically same. For example, the *component name* of a component may have aliases, but all these aliases refer to the same component.

Thus, the integration of the values may be the *mapped* value from the original values, *intersection* of the values, *mathematical operation* and so on. Which strategy should be taken depends on the domain information.

3.5 Theorems and Properties

COROLLARY 1 (CLOSURE OF MERGING). (1) The merging of the two CSP_σ actions by Procedure 4 produces another CSP_σ action and (2) the integration of two attributes by Procedure 5 produces another attribute.

THEOREM 1 (PRESERVATION OF SEMANTICS). The semantics of the integrated BM by Procedures 1, 2 and 3 is consistent with the semantics of the given two input BMs.

THEOREM 2 (POLYNOMIAL COMPLEXITY). Given two BMs having edge sets E_1 and E_2 , the worst-case complexity of (1) Procedure 1 is $O(\min(e_1, e_2))$, (2) Procedure 2 is $O(e_2)$ and (3) Procedure 3 is $O(1)$, $e_1 = |E_1|$, $e_2 = |E_2|$.

THEOREM 3 (CLOSURE OF MERGING CSP_σ PROCESSES). The merging of the two CSP_σ processes by Procedures 1, 2 and 3 also produce a CSP_σ process.

THEOREM 4 (OPTIMAL REFINEMENT). Procedures 1, 2 and 3 produce an optimally refined CSP_σ process from the given two CSP_σ processes.

Properties of the merging of CSP_σ processes: We get the following properties:

- 1) *Reflexive:* $P_{u_i} \oplus P_{u_i} = P_{u_i}$.
- 2) *Asymmetry:* $P_{u_i} \oplus P_{u_j} \neq P_{u_j} \oplus P_{u_i}$.
- 3) *Partial Symmetry:* $P_{u_i} \oplus P_{u_j} = P_{u_j} \oplus P_{u_i}$ if the corresponding BMs have root-root relation.
- 4) *Associative:* $P_{u_i} \oplus P_{u_j} \oplus P_{u_k} = (P_{u_i} \oplus P_{u_j}) \oplus P_{u_k} = P_{u_i} \oplus (P_{u_j} \oplus P_{u_k})$.

Properties of the merging of CSP_σ actions, edges and attributes: Each operation shares the same set of properties. We mention the properties for CSP_σ actions:

- 1) *Reflexive:* $u_i \oplus u_i = u_i$.
- 2) *Symmetric:* $u_i \oplus u_j = u_j \oplus u_i$.
- 3) *Associative:* $u_i \oplus u_j \oplus u_k = (u_i \oplus u_j) \oplus u_k = u_i \oplus (u_j \oplus u_k)$.

Proofs will be available in the longer version of the paper.

4. INTEGRATION OF A SET OF BMS

In this section, we use an SNM of the interrelated BMs and develop an algorithm to integrate all the BMs into one BM. Let, m_1 to m_7 denote the BMs of the SAS. Suppose they are interrelated to each other as shown in Table 1. The column BMs shows the pair of parent and child BMs, Relations($u_p, \odot$) shows the type of relation, parent BU (u_p) and the similarity measure ($\odot$) of the parent and child BUs.

Table 1: Relations of the BMs of the SAS.

BMs	Relations($u_p, \odot$)	BMs	Relations($u_p, \odot$)
m_2, m_3	leaf-root($u_3, 1$)	m_2, m_4	leaf-root($u_3, 1$)
m_3, m_4	root-root($u_0, 1$)	m_4, m_3	root-root($u_0, 1$)
m_4, m_5	leaf-root($u_2, 1$)	m_6, m_2	leaf-root($u_2, 1$)
m_5, m_6	branch-root($u_2, .75$)	m_5, m_7	branch-root($u_2, .75$)
m_6, m_7	root-root($u_0, 1$)	m_7, m_6	root-root($u_0, 1$)
m_3, m_1	root-root($u_0, 1$)	m_1, m_3	root-root($u_0, 1$)
m_4, m_1	root-root($u_0, 1$)	m_1, m_4	root-root($u_0, 1$)
m_2, m_1	leaf-root($u_3, 1$)	m_5, m_2	branch-root($u_4, 1$)

Fig. 9 shows a sample SNM created from the Table 1. We assumed that m_2 is the initialisation (Init) model. Initially, m_2 is IN, and all other BMs are EX. For a BM, we assign

confidence 1 if a BM is IN and 0 if EX. Otherwise, confidence of a BM is the confidence of its parent multiplied by the similarity measure of its corresponding integration relation. Further, a relation is annotated by its acceptability state. We consider two layers of thresholds namely (1) IN threshold α_{IN} and (2) UN threshold α_{UN} where $\alpha_{UN} < \alpha_{IN}$. We assume a relation is IN if similarity $\geq \alpha_{IN}$, and EX if similarity $< \alpha_{UN}$, and UN otherwise. Assume that $\alpha_{IN} = 1$ and $\alpha_{UN} = 0.75$.

Figure 9: SNM showing initial states, relation equivalences and confidence levels

The acceptability states of the other BMs can be inferred. For example, m_2 is IN and the relation between m_2 & m_3 is also IN. Therefore, m_3 can be inferred as IN. We infer UN(m) if it is not IN and there exists at least one pair of parent and relation such that both are not EX. We infer EX(m) if it is neither IN nor UN. Further, The SNM shown in Fig. 9 can be made well-formed by eliminating redundant relations, breaking cycles and assigning the states as shown in Fig. 10. Assume that the relations between m_5 & m_6 and m_5 & m_7 have been accepted by the requirements analyst. Informally, we say an SNM is well-formed, if (1) the SNM is a directed acyclic graph, (2) the number of Init models in the SNM is 1, (3) all models are IN, and (4) all existing relations are IN [3]. We use $childs(m_i)$ and $parents(m_i)$ to denote child and parent BMs respectively.

Figure 10: well-formed SNM

We can traverse the well-formed SNM from the Init model by breadth first search, and integrate the BMs into one BM.

PROCEDURE 6 (INTEGRATING BMS). Given a well-formed SNM $G = \langle \mathcal{M}, \mathcal{R} \rangle$ where $\mathcal{M}$ is the set of BMs and $\mathcal{R}$ is the set of relations in the well-formed SNM, the integration of the BMs are performed by Algorithm 1.

Algorithm 1: integrateBMs(G)

```

push Init BM to an empty  $Q$ ;
init  $I_m = \text{Init BM}$ ; // Integrated Model
while  $Q$  is not empty do
  pop  $m_i$  from  $Q$ ;
  foreach  $m_j \in \text{childs}(m_i)$  do
    foreach equivalent BUs pair ( $u_p, u_c$ ) do
       $I_m = I_m \oplus m_j$ . (Procedure 1, 2 or 3)
    foreach ( $m_i, m_k$ )  $\in \mathcal{R}$  do
      push  $m_k$  to  $Q$ ;
return  $I_m$ 

```

THEOREM 5 (POLYNOMIAL COMPLEXITY). Given relations $\mathcal{R}$ in the well-formed SNM G , the worst-case complexity of Algorithm 1 (integrateBMs) is $O(r)$, $r = |\mathcal{R}|$.

THEOREM 6 (SOUNDNESS & COMPLETENESS). (1) Given a well-formed SNM, Procedure 6 produces an integrated BM in polynomial time, (2) Procedure 6 can be applied to any well-formed SNM to produce an integrated BM.

5. RELATED WORK

We classify the related work into two categories: *Formalisation of BE*, and *Integrating Software Models*.

Formalisation of BE: Colvin and Hayes [4] provided the semantics of the BT using CSP_{σ} . We extended the semantics by including the edge between nodes as an entity in CSP_{σ} . Winter et al. [24] developed a framework of rules for integrating requirements using a notation-independent graphical model. Though they discussed overall broad approach of BTs integration, the rules do not relate the integration with BT's semantics. They also did not develop the techniques to automatically integrate a set of BTs.

BT has been used for model-checking to assess the safety requirements [12], analyse role-based access control [26], perform Failure Modes and Effects Analysis (FMEA) [8], to identify the combinations of component failures by Cut Set Analysis (CSA) [11], verify large systems using a slicing techniques [25] and so on. Myers et al. [16] simulated behavioral scenarios using BTs into Modelica framework.

Integrating Software Models: In earlier stage ([9], [13]), the main focus was to do parallel composition of models that explains how two different components work together. Since different UML diagrams have different syntax and semantics, merging of those models are mostly manual ([7], [22]). Uchitel and Chechik [21] worked on merging two partial behavioral models of the same component to produce an elaborated version of both original models. Our works differ from these works in composing two behavioral models depicting state-based and scenario-based behavioral scenarios of more than one interacting components of the software system, which may have overlapping system behaviors, to obtain a more compact version of the original two.

6. CONCLUSION

In this paper, we provided a formal definition of the integration of the BTs. We first formalised the semantic integration of two interrelated BTs using an extended version of CSP_{σ} . We then formalised the integration of a set of BTs. Our future research focus is to formalise specification process where we would like to semi-automate the tasks to convert an integrated BT into a specification BT which can be validated by simulation and verified by model-checking.

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