Robust Interactions under System Crashes and Network Failures of Collaborative Processes with Arbitrary Control Flows

Lei Wang,
Luís Ferreira Pires
and Marten J. van Sinderen

CTIT, University of Twente,
the Netherlands
Emails: {l.wang-1, l.ferreirapires, m.j.vansinderen}@utwente.nl

Andreas Wombacher

Achmea, the Netherlands
Postbus 866
3700 AW Zeist
Email: andreas.wombacher@achmea.nl

Chi-Hung Chi

CSIRO, Australia
3-4 Castray Esplanade,
Hobart, Tasmania, 7000
Email: chihungchi@gmail.com

***Abstract*—Due to the possibility of system crashes and network failures, the design of robust interactions for collaborative business processes is a challenge. If a process changes state, it sends messages to other relevant processes to inform them about this change. However, server crashes and network failures may result in a loss of messages. In this case, the state change is performed by only one process, resulting in global state/behavior inconsistencies and possibly deadlocks. Our idea to solve this problem is to (automatically) transform the original processes into their robust counterparts. We illustrate our solution using a subset of WS-BPEL. A WS-BPEL process is modeled using a so called Nested Word Automata (NWA), to which we apply our transformation solution and on which we perform correctness proof. We have also analyzed the performance of our prototype implementation. In our previous work, we assumed that a certain pre-defined interaction follows the failed interaction. In this work, we lift this limitation by allowing an arbitrary behavior to follow the failed interaction, making our solution more generally applicable.**

Keywords–robust, collaborative processes, WS-BPEL, interactions, system crash, network failure, automata

I. INTRODUCTION

The electronic collaboration of business organizations has grown significantly in the last decade. Often data interchange is based on processes run by different parties exchanging messages to synchronize their states. If a process changes state, it sends messages to other relevant processes to inform them about this change. However, server crashes and network failures may result in a loss of messages. In this case, the state change is performed by one process, resulting in global state/behavior inconsistencies and possible deadlocks. In general, a state inconsistency is not recovered by the process engine that executes the process. This can be seen from a screen dump of errors from the Oracle process engine 12c which sends message to an unavailable server (see Figure 1).

Figure 2a shows that normally, a business process is deployed to a process engine, which runs on the infrastructure services (OS, database, networks, etc.), where system crashes and network failures may happen. Our solution to recover from failures is to transform business processes into their robust counterparts, as shown in Figure 2b. The robust process is deployed on the unmodified infrastructure services and is recoverable from some interaction failures caused by system crashes and network failures. Our solution has the following properties: (1) the application protocols are not modified. We do not modify the message format nor message sequence, e.g., by adding message fields that are irrelevant for the application logic or adding acknowledge messages to the original message sequence. The service autonomy is kept in that if one party transforms the process according to our approach and the other party does not, they can still interact with each other, although without being able to recover from system crashes and network failures. (2) the process transformation is transparent for process designers. In this paper, we illustrate our solution using WS-BPEL [1]. However, other process languages may be applicable as long as they support similar workflow patterns [2].

This paper is an extension of our previous work [3][4][5][6], where we assumed that a certain pre-defined interaction follows the failed interaction, i.e., the only sequence control is assumed that the further interaction is sequentially following the failed interaction. A technical report [7] is provided as an online version with more details on the formalism used and the transformation methods of our approach. In this paper, we lift this limitation by allowing an arbitrary behavior to follow the failed interaction, making our solution more generally applicable. We support conditional control flow and loops and their arbitrary combination as possible further interaction after interaction failure. The structure of the paper is the following: Section II analyzes possible interaction

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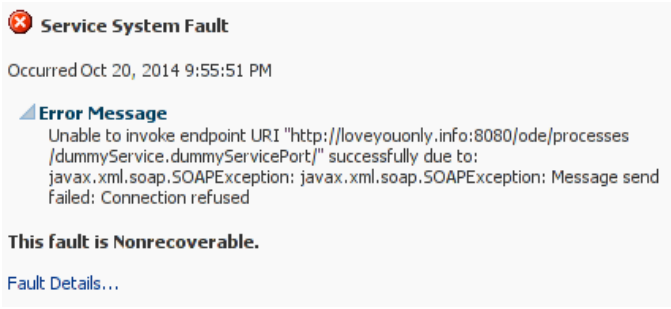
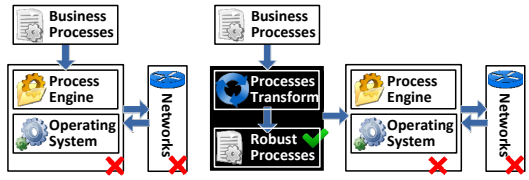
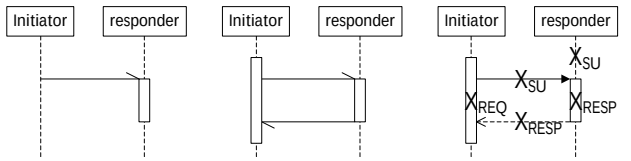


Figure 1. Oracle SOA engine interaction errors.



(a) Interaction failures (b) Robust process transformation

Figure 2. Our idea to cope with failures.



(a) *send* and *receive* (b) *send-receive* case I (c) *send-receive* case II

Figure 3. Process interaction patterns.

failures. Section III proposed our process transformation-based solution. Section IV validates our solution. Section V discusses related work and Section VI concludes our paper.

II. Interaction Failure Analysis

This section analyzes possible interaction failures of collaborative processes caused by system crashes and network failures.

A. Process Interaction Patterns

Process interaction failures are specific to interaction patterns. In [8], 13 interaction patterns are identified. In this paper, we focus on the *send*, *receive* and *send-receive* patterns. This limitation is not severe because more complex patterns can be composed using these basic interaction patterns. Figure 3a shows an initiator that sends a one-way message to a responder. The initiator behavior corresponds to the *send* pattern, while the responder behavior corresponds to the *receive* pattern. In pattern *send-receive* in Figure 3b the initiator combines one *send* and one *receive* pattern. We call this pattern asynchronous interaction in the sequel of the paper. In Figure 3c, the initiator starts a synchronous interaction by sending a request and getting a response, which characterize the *send-receive* pattern.

B. Process Interaction Failures

Interaction failures caused by system crashes and network failures are *pending request failure*, *pending response failure* and *service unavailable* [4]. As all failures possible in the interaction patterns of Figure 3a and Figure 3b are covered by Figure 3c, we look only into the interaction failures of the interaction pattern in Figure 3c. *Service unavailable* (marked as X_{SU}) is caused by a responder system crash or a network failure of the request message delivery. At process level, the initiator is aware of the failure through a catchable exception of the process implementation language. *Pending request failure* (marked as X_{REQ}) is caused by initiator system crashes after sending a request message. The initiator is informed of the failure after restart, e.g., through catchable exceptions. However, the responder is not aware of the failure, so that it replies with the response message and continues execution. *Pending response failure* (marked as X_{RESP}) is caused by a responder system crash or a network failure of the response message delivery. In both cases, the responder replies with the response message (after a restart if the responder system crashes) and continues execution. However, the connection gets lost and the initiator cannot receive the response message. The initiator is aware of this failure after a timeout.

Due to the heterogeneous infrastructure, e.g., different process engine implementations or network environments, we have to make the following assumptions concerning the failure behavior of the infrastructure: *1) Persistent execution state.* The state of a business process (e.g., values of process variables) are kept persistent and survive system crashes. *2) Atomic activity execution (e.g., invoke, receive, reply).* A system crash means that the execution is stopped only after the previous activity is finished and the next activity has not started. A restart means that execution resumes from the previous stopped activity. These assumptions correspond with the default behavior of the most popular process engines, such as Apache ODE or Oracle BPEL Process Manager (released as a component of Oracle SOA Suite). In Apache ODE's term, this is named as persistent processes in their default configuration. Otherwise this configuration can be modified to "in-memory" at deployment time [9]. For Oracle BPEL Process Manager, this is named as "durable" processes, otherwise is named as "transient" processes. By default all the WS-BPEL processes are durable processes and their instances are stored in the so called dehydration tables, which survives system crashes [10]. *3) Network Failures* interrupt the established network connections and the messages that are in transit get lost.

III. Process Transformation Based Solution

A. Business Processes

We choose WS-BPEL as process specification language in our work. A WS-BPEL process is a container where relationships to external partners, process data and handlers for various purposes and, most importantly, the activities to be executed are declared. As an OASIS standard, it is widely used by enterprises. We use Nested Word Automata (NWA) [11] to describe the underlying semantics of WS-BPEL and use them as a basis for our formal evaluation. We choose NWA because we need to model the nested structure of WS-BPEL syntax. While traditional finite state automata can be used for

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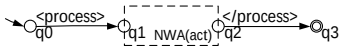
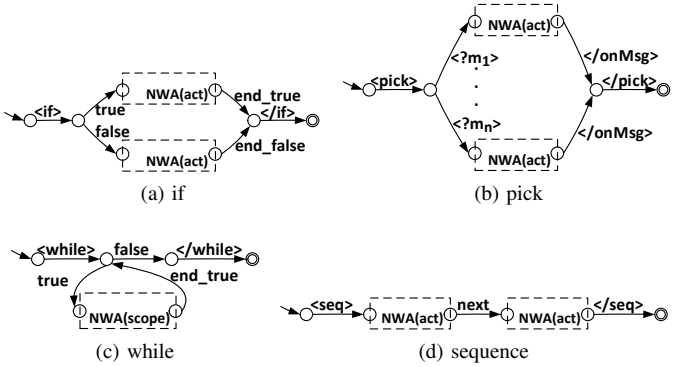
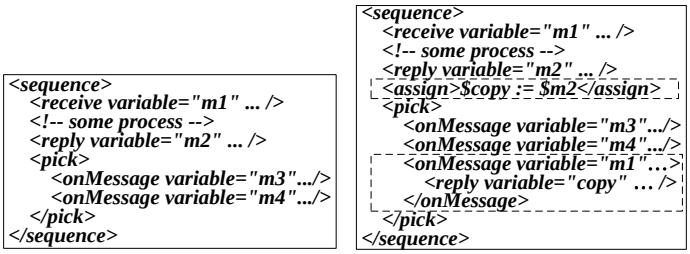


Figure 4. NWA model of a process.



(a) if (b) pick (c) while (d) sequence

Figure 5. NWA model of WS-BPEL structured activities.



(a) example WS-BPEL snippet (b) transformation, step I

Figure 6. WS-BPEL example of our solution.

describing all possible states of messages, and their sending and receiving sequences, they lack the capability of describing nested structures of activities.

An NWA is an automaton that has hierarchical nesting structures. Formally, an NWA A over an alphabet Σ is a structure $(Q, q_0, Q_f, P, p_0, P_f, \delta_c, \delta_i, \delta_r)$ consisting of
- a finite set of (linear) states Q,
- an initial (linear) state $q_0 \in Q$,
- a set of (linear) final states $Q_f \subseteq Q$,
- a finite set of hierarchical states P,
- an initial hierarchical state $p_0 \in P$,
- a set of hierarchical final states $P_f \subseteq P$,
- a call-transition function $\delta_c : Q \times \Sigma \mapsto Q \times P$,
- an internal-transition function $\delta_i : Q \times \Sigma \mapsto Q$, and
- a return-transition function δ_r: $Q \times P \times \Sigma \mapsto Q$.

The definition of Q, q_0, Q_f, δ_i corresponds to the definition of a finite state automata over an alphabet Σ [12]. The alphabet Σ represents all possible process behaviors, e.g., $<$*process*$>$ $\in \Sigma$ represents the starting of a business process, $?m_i \in \Sigma$ represents receiving a message while $!m_j \in \Sigma$ represents sending a message. An internal transition $\delta_i(q_i, !m_i) = q_j$ represents that the process replies a message $!m_i$ at the state q_i and then enters the state q_j. The hierarchical states P, p_0, P_f are used to describe the nesting structure of an NWA. A *call transition* δ_c enters the nested automaton while a *return transition* δ_r leaves the nested automaton. A nested structure is graphically represented as dashed box. The NWA model of a WS-BPEL process is shown in Figure 4. A call transition $\delta_c(q_0, <$*process*$>) = (q_1, p_a)$ starts from the initial state and a return transition $\delta_r(q_2, p_a, <$*/process*$>) = q_3$ leads to the accepted state. The NWA model of an activity *NWA(act)* is nested within the NWA of the process. This is described by the hierarchical state p_a.

WS-BPEL activities are divided into two categories, namely *basic* and *structured* activities. The currently supported *structured* activities are *if*, *pick*, *while* and *sequence*, as shown in Figure 5. The *flow* (concurrent execution) or the other forms of loops (*RepeatUntil, ForEach*) are not considered now and will be considered in future work. Each structured activity model has exactly one call transition and one return transition to *enter* and *leave* its nested structure(s), which is represented as a dash box. The detailed explanation of our formalization is presented in [7].

B. Transformation Method

An operation that can be safely repeated is called idempotent [13]. Idempotent operations can be recovered by resending the request message. However, a request resent to non-idempotent operations (such as bank transfer operations) triggers potentially incorrect executions. Our solution for non-idempotent operation is that when a failure happens, a resent message is replied with a copy of the previous processing result.

In the example of Figure 6a, the WS-BPEL snippet receives a message $m1$, performs some (non-idempotent) processing, then replies with a message $m2$. The next incoming messages could be $m3$ or $m4$. If the initiator sends request $m3$ or $m4$, this implies that the initiator has successfully received the response message $m2$. If due to an interaction failure, for example, the initiator crashes and fails to receive the response message $m2$, the initiator can recover by resending request message $m1$. We then transform the responder process to use a copy of the previous result as response. Figure 6b shows that in order to make a copy of the response message, we use an *assign* activity to keep the result value in a process variable $\$copy$. In the *pick* activity, we add an *onMessage* branch to accept the resent message $m1$ and use the variable $\$copy$ as the response. However, a resent message could be sent multiple times before the response is ultimately received. We nest the *pick* activity in a *while* to cope with the duplicate resent message. A detailed discussion is in [7]. Our process transformation algorithm is presented as follows.

1) Responder Transformation Algorithm: For a WS-BPEL process, given its *NWA* model $(Q, q_0, Q_f, P, p_0.P_f, \delta_c, \delta_i, \delta_r)$ over the alphabet Σ, we assume that the alphabet that represents the response messages is Σ_{resp} and the alphabet that represents the request messages is Σ_{req}, thus $\Sigma_{req} \subseteq \Sigma$ and $\Sigma_{resp} \subseteq \Sigma$. The transformation algorithm is as Figure 7.

The algorithm iterates through all combinations of a state q, a request message $?m_{req}$ and a response message $!m_{resp}$. In line 2, we check if the message pair $(?m_{req}, !m_{resp})$ corresponds to the request and response for a synchronous operation and at state q, the response message $!m_{resp}$ is sent,

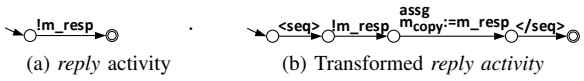
1: **for all** $q \in Q$, $?m_{req} \in \Sigma_{req}$ **and** $!m_{resp} \in \Sigma_{resp}$ **do**
2: **if** (m_{req}, m_{resp}) is a synchronous message pair **and** $\delta_i(q, !m_{resp})$ is defined in *NWA* **then**
3: $save\_reply(q, !m_{resp})$
4: N $\leftarrow next\_receive(q, !m_{resp})$
5: **for all** $?m_{next} \in N$ **and** $q_{next} \in Q$ **do**
6: **if** $\delta_i(q_{next}, ?m_{next})$ is defined in *NWA* **then**
7: $transform\_receive(q_{next}, ?m_{next})$
8: **else if** $\delta_c(q_{next}, ?m_{next})$ is defined in *NWA* **then**
9: $transform\_pick(q_{next}, ?m_{next})$
10: **end if**
11: **end for**
12: **end if**
13: **end for**

Figure 7. Responder process transformation algorithm

represented by a transition $\delta_i(q, !m_{resp})$. This is the failure point that the response message may be lost due to interaction failures and where our transformation method applies. As defined in line 3, we first make a copy of the response message, as shown in Figure 8. The NWA model of *reply* activity in Figure 8a is replaced by an NWA model of a *sequence* activity in Figure 8b, in which a *reply* activity model and an *assign* activity model are nested. The *assign* activity model represents the copy of the reply message into the variable m_{copy}. In order to process the possible resent request message $?m_{req}$ due to the lost of the message $!m_{resp}$ sent at state q, we calculate the set of all possible next incoming messages, which is defined as $next\_receive(q, !m_{resp})$ in line 4. We construct an automaton $A(!m_{resp}, ?m_{next})$ as in Figure 9 to describe that a process replies with a message $!m_{resp}$ and waits for some possible next incoming message $?m_{next}$. $\delta(q_0, !m_{resp}) = q_1$ models the reply of the response message $!m_{resp}$. $\delta(q_1, \Sigma/\Sigma_{req}) = q_1$ represents some process execution in which no messages are received. $\delta(q_1, ?m_{next}) = q_2$ represents that the process receives an incoming message $?m_{next}$. $\delta(q_2, \Sigma) = q_2$ models any process execution. For the process *NWA* model, at some state q, a reply of a message $!m_{resp}$ is represented by an internal transition $\delta_i(q, m_{resp})$. We change the initial state of the process *NWA* model to from q_0 to q, and call this automaton *NWA*(q). Starting at q, after replying the message $!m_{resp}$, if one possible next incoming message is $?m_{next}$, then *NWA*$(q) \cap A(!m_{resp}, ?m_{next}) \neq \emptyset$, i.e., the process modeled by *NWA* has the behavior described by $A(!m_{resp}, ?m_{next})$.

The intersection operation $\cap$ between an *NWA* and an finite state automaton is defined to check whether the business process modeled by the *NWA* has the message sending and receiving behavior modeled by the automaton. The intersection operation is based on finite state automata. We "flatten" an *NWA* to a finite state automaton by skipping hierarchical information, described as follows. Given a NWA $(Q, q_0, Q_f, P, p_0, P_f, \delta_c, \delta_i, \delta_r)$ over the alphabet Σ, the "flattened" automaton is $A(Q, q_0, Q_f, \Sigma, \delta)$, where Q, q_0, Q_f and Σ are the same as the NWA, the transition function δ is defined as

1) $\delta(q_{i1}, a) = q_{i2}$, if the NWA has an internal transition $\delta_i(q_{i1}, a) = q_{i2}$.
2) $\delta(q_{c1}, a) = q_{c2}$, if the NWA has a call transition $\delta_c(q_{c1}, a) = (p, q_{c2})$.



(a) *reply* activity (b) Transformed *reply activity*

Figure 8. Responder process transformation, *reply* activity.

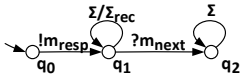
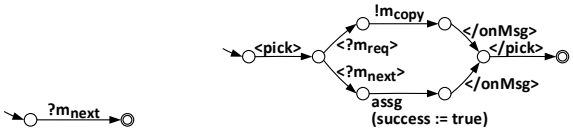
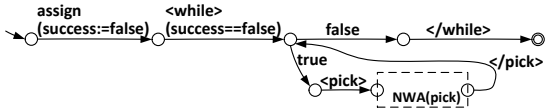


Figure 9. The automaton $A(!m_i, ?m_{next})$.



(a) Responder, *receive* activity (b) Transformed responder, part I



(c) Transformed responder, part II

Figure 10. Responder process transformation, *receive* activity.

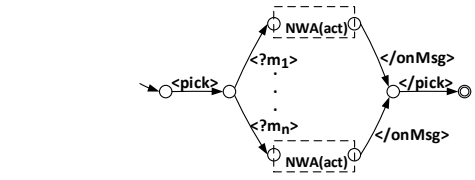
3) $\delta(q_{r1}, a) = q_{r2}$, if the NWA has a return transition $\delta_r(q_{r1}, p, a) = q_{r2}$.

Both call transitions and return transition are treated as flat transitions that the hierarchical state p is not considered. The intersection operation can be done between two finite state automata, as defined in [12].

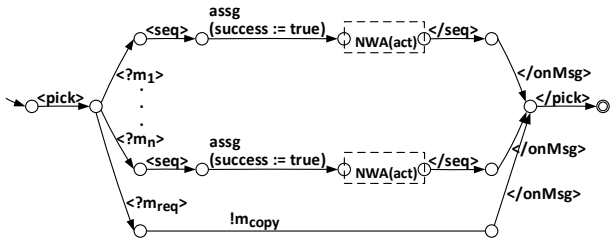
We define the set of all possible next incoming messages as $next\_receive(q, !m_{resp}) = \{?m_{next} | ?m_{next} \in \Sigma_{req} \wedge$ *NWA*$(q) \cap A(!m_{resp}, ?m_{next}) \neq \emptyset\}$.

For all $?m_{next} \in next\_receive(q, !m_{resp})$ and $q_{next} \in Q$, if at the state q_{next} the next incoming message $?m_{next}$ is received, two cases of transition may be defined in *NWA*: in a model of a *receive* activity as an internal transition $\delta_i(q_{next}, ?m_{next})$ or in the model of a *pick* activity as a call transition $\delta_c(q_{next}, ?m_{next})$. For the first case (line 6), as shown in Figure 10a, the procedure $transform\_receive(q_{next}, ?m_{next})$ is introduced as follows. We replace the transition with a *pick* activity with two branches, as shown in Figure 10b. One *onMessage* branch models the receive of the resent message $?m_{req}$ and the reply of the result message m_{copy}. The other *onMessage* branch models the receive of the message $?m_{next}$, and after that we set the flag $success$ to $true$ to indicate that the previous interaction is finished successfully. However, a possible loss of the response message m_{copy} triggers multiple resending of the request m_{req}. Therefore, the *pick* activity is defined in a *while* iteration so that multiple requests $?m_{req}$ can be accepted. Figure 10c shows that the *while* iteration ends when the flag $success$ is set to *true*.

For the second case (line 8), as shown in Figure 11a, the message $?m_{next}$ is one of the messages in $m_1, ..., m_n$. Figure



(a) Responder, *pick* activity



(b) Transformed responder, part I

Figure 11. Responder process transformation, *pick* activity.

11b shows that we then add a call transition $<?m_{req}>$ to model that the process accepts the resent message, and an internal transition $!m_{copy}$ to represent the reply using a copy of the previously cached result m_{copy}. In the other branches, the nested NWA(act) is replaced by the model of a *sequence* activity, in which we model the assignment of the flag variable *success* to *true*, followed by the original NWA(act). Similarly, in order to cope with a possible loss of the response message m_{copy}, the *pick* activity model is nested in a *while* iteration to handle multiple resent messages, as shown in Figure 10c. We do not directly prove the correntness of this algorithm, however, the correctness of the transformed processes by this algorithm have been proved in section IV.

After the transformation, at some states the responder can receive more messages than the original process, because the resent message can be accepted and be replied. However, the request is not processed again. In this sense, we do not give malicious initiators any chance of jeopardizing the process by changing the sequence of requests or sending the same request multiple times.

2) Initiator Transformation: The initiator transformation makes it resend the request message whenever a failure happens. The detailed transformation method is presented in [7].

3) Recoverable Assumption: Assume that $(?m_{req}, !m_{resp})$ is a pair of synchronous request and response messages, the process receives request message $?m_{req}$, then at state q, the process sends the response message $!m_{resp}$. However, if $?m_{req} \in next\_receive(q, m_{resp})$, then one of the next possible messages is still $?m_{req}$, in this case, the responder cannot distinguish a resent message due to a failure from a normal request message. Thus we have to require that in the process design the condition $?m_{req} \notin next\_receive(q, !m_{resp})$ can be met. However, by following a few process design principles during the design of the original process, this condition can be met. An example is, a split of message $?m_{req}$ into two different messages, $?m_{req1}$ and $?m_{req2}$ (for example, one message is used to send request, the other asks for results). The initiator sends the two messages back to back. If a responder receives $?m_{req1}$, then it waits for $?m_{req2}$, rather than waiting for $?m_{req1}$ again.

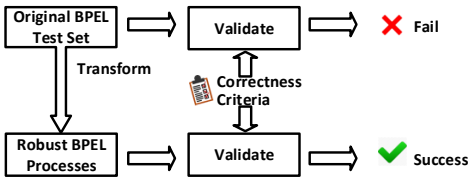


Figure 12. The setup of the correctness proof.

IV. EVALUATION

This section presents the correctness validation of our solution. We also evaluate the performance overhead of our prototype under different workloads.

A. Correctness Validation

The correctness proof shows that the solution introduced in Section III provides a robust process. The core of the proof is to define the correctness criteria for asynchronous and synchronous interactions and represent them such that they can be automatically evaluated.

Figure 12 shows the setup of our correctness proof. We take the test set of 726 example WS-BPEL processes which implement all possible Internet Open Trading Protocol (IOTP) interactions [14], and we transform them into the *NWA* model of the corresponding robust business process. The proof is finished by checking that the *NWA* process model is a subset of the correctness criteria, which are modeled as automata. Given an automaton $A(Q, \Sigma, \delta, q_0, F)$, each state in Q represents a state of the messages sending and receiving status. Set Σ models of all possible process behaviors, e.g., sending and receiving messages. δ is transition function: $Q \times \Sigma \rightarrow Q$ that models the state transition triggered by process execution, e.g., for states $q_i, q_j \in Q$ and $!m \in \Sigma$, $\delta(q_i, !m) \rightarrow q_j$ represents that at state q_i, the process replies with message $!m$ and then enters state q_j. The correctness criteria automata models the set of correct message sending and receiving sequences. We present the correctness criteria as follows.

1) Initiator Side Correctness Criteria: There are two criteria due to the interaction patterns: the criteria for a single message sending and the criteria for synchronous request and response message pair. In this paper, we discuss only the latter due to the page limitations. The automaton is visualized as Figure 13a. A correct interaction is regarded as, a request message $?m1$ can be sent at state q_0 and can be resent multiple times at state q_1 until a response message $!m2$ is received at state q_2.

2) Responder Side Correctness Criteria: The property we want to validate is that any resent message can be accepted by the transformed process and replied. Given a process, assume that the synchronous request and response messages are m_j and m_i. If the transformed robust process model is NWA', for state q_i and transition $!m_i$, we have $?m_j \in next\_receive(q_i, !m_i)$. The idea behind it is that after the reply message $!m_i$ is sent, the robust process can accept possible resent messages due to failures. In this case, the response should be sent without reprocessing. The criteria are shown

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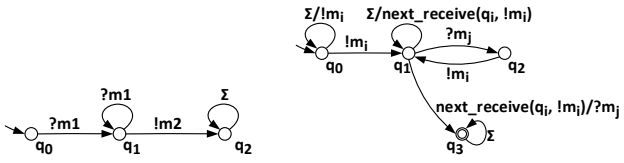
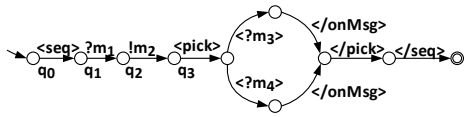
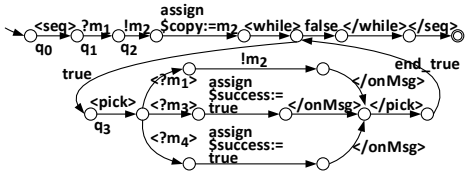


(a) Initiator (b) Responder

Figure 13. Correctness criteria of process transformation.



(a) Automaton model of the original process



(b) Automaton model of the transformed process

Figure 14. Illustration of the correctness validation, robust *NWA* model of Figure 6.

as Figure 13b. We omit the detailed discussion of this criteria due to page limitations.

The process control flows can be designed in arbitrary ways, and since we cannot exhaust all possibilities, we use a WS-BPEL test set that implements all possible IOTP interactions, which is a total of 726 BPEL processes. After the transformation of the test processes into automata, we apply the subset check to evaluate the correctness of the WS-BPEL test processes, i.e., we prove that for all processes and their *NWA* model and criteria automaton A, *NWA* $\in A$, i.e., all messages sending and receiving sequences are correct.

We take the process in Figure 6 to illustrate the correctness validation. An original WS-BPEL snippet shown in Figure 6a is transformed into the robust counterpart, and their automata models are shown as Figures 14a and 14b, respectively. At state q_2, where the message $!m_2$ is to be replied, the set of the possible next incoming messages of the responder is $next\_receive(q_2, !m2) = \{?m1, ?m3, ?m4\}$. The criteria for the synchronous request $?m1$ and the response $!m2$ is shown as Figure 15. First, we do a subset check to prove that the original is not a subset of the criteria. Actually, we can see that the message sequence $(.., ?m1, !m2, .., ?m1, !m2, ..?m3, ..)$ can be accepted by the criteria automaton. However, this sequence cannot be accepted by the model of the original process, since there is no transition defined for the second $?m1$. Second, we do a subset check to prove the transformed automata model is a subset of the criteria, i.e., all sending and receiving message sequences are correct.

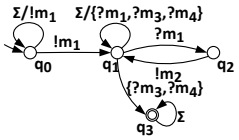


Figure 15. Correctness criteria for the illustrative process.

Figure 16. Setup of Performance Test.

TABLE I. PERFORMANCE OVERHEAD.

Origin	Trans	Overhead	Origin	Trans	Overhead
Workload $\lambda = 5$			Workload $\lambda = 10$		
287 ms	379 ms	92 ms	322 ms	452 ms	130 ms

B. Performance Evaluation

In Figure 2 of the whole setup, if the infrastructure (OS, process engine, hardware and network configuration) is the same, performance depends mainly on the process design and the workload, i.e., $performance = Test(ProcessDesign, workload)$.

We use similar setup of our performance test with our previous performance tests [15], which is shown in Figure 16. We use the cloud infrastructure from Amazon EC2. The initiator and responder processes are deployed on two computing instances and we use a local client to collect the performance data.

We evaluated the performance overhead of our transformed process under different workloads. The number of requests sent per minute by the local client complies with a Poisson distribution with parameters $\lambda = 5$ and $\lambda = 10$ requests per minute. We used these workloads because according to our tests under the available hardware and software configurations, higher workloads would exhaust the server resources. We use the open source Apache ODE process engine where an embedded Derby [16] database is used. The Amazon EC2 instance type is t1.micro with 1 vCPU and 0.594GiB memory. Each test run lasted for 60 minutes, but only the response times in the 30 minutes in the middle of this period have been considered (steady state).

The performance data is shown as Table I. Under the workload of $\lambda = 5$, the average performance overhead of our transformation mechanism is 92 ms. Under the workload of $\lambda = 10$, the average overhead is 130 ms. We conclude then that the performance overhead increases with the workload. However, we expect lower performance overhead when the infrastructure is scalable, like in a cloud environment.

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V. Related Work

Solutions based on exception handling [17][18] is process-specific. WS-BPEL supports compensations of well-defined exceptions using exception handlers. However, elaborate process handler design requires process-specific knowledge of failure types and their related recover strategies. Alternatively, we try to ease the process designers from dealing with synchronization failures by a transparent process transformation from a given business process to its recovery-enabled counterpart.

A fault tolerant system can be built by coping with the occurrence of failures by applying redundancy [13]. Three kinds of redundancy are possible: information redundancy, time redundancy and physical redundancy. However, the existing solution either require more effort of the business process designers, or additional infrastructure support, or both.

On physical layer, the robust solutions on process engine level [19][20] dependend on a specific process engine. We defined our solution based on the WS-BPEL building blocks without requiring extensions at the engine level. However, the transformed process can still be migrated to other standard process engines. Reliable network protocols such as HTTPR have been proposed to provide reliable synchronization. However, the deployment of these solutions increases the complexity of the network infrastructure. We assume that system crashes and network failures are rare events, thus extending the infrastructure may introduce too much overhead. Further, the solutions are not applicable in some outsourced deployment environments. For example, in some cloud computing environments, user-specific infrastructure configuration to enhance synchronization is not possible. Dynamic service substitution [21][22] is a way to perform recovery by replacing the target services by equivalent services. In [23][24], the QoS aspects of dynamic service substitution are considered. In our work, we do not change the business partners at runtime.

Information redundancy recovery is based on replication. Our cache-based process transformation is information redundant because a cache is a kind of replication. Time redundancy solutions include web services transactions. The WS-AT [25] standard specifies atomic web services transactions, while WS-BA [26] standard specifies relaxed transactions so that the participant can choose to leave the transaction before it commits. However, if a transaction rolls back, a process-specific compensation is required. Actually, transactions can deal with well-defined failures. The 2-phase commit distributed transaction protocol can not deal with system crash (referred to as *cite failure* in [27]). However, in a special case of process in which all participants send vote results to a coordinator, if the coordinator crashes before sending the vote results to any participant, all the participants are blocked and the final results of the transaction remain unknown.

VI. Conclusion and Future Work

In this paper, we have identified three types of interaction failures caused by system crashes and network failures and we have proposed a process interaction failure recovery method to cope with system crashes and network failures. This paper is an extension of our previous work [3][4][5][6], where we assumed that a certain pre-defined interaction follows the failed interaction. In this paper, we lift this limitation by allowing an arbitrary behavior to follow the failed interaction, making our solution more generally applicable. The challenge is to accept the resent message due to failures with the arbitrary control flow of the responder process. We transformed the business process design into nested word automata model. At a state that models the reception of an incoming message, we add an additional transition to accept the resent message due to failure. We have proved the correctness of our process transformations and we implemented a prototype to test the runtime performance of our method. Currently, the transformation process is semi-automatic. We have implemented the automatic transformation from a WS-BPEL process to the NWA model, however, the transformation of the NWA model to the robust counter part is manually. In future, we will automate the transformation process and we will investigate more complex process interaction patterns.

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