Fault-Tolerant and Scalable Protocols for Replicated Services in Mobile Agent Systems^{*}

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Abstract. To enhance scalability of replicated services a large number of mobile agents attempt to access in mobile agent systems, we present a new strategy to apply an appropriate passive replication protocol to each replicated service according to its execution behavior because deterministic services require weaker constraints to ensure their consistency than non-deterministic ones. For this goal, two passive replication protocols are introduced for non-deterministic services and for deterministic services respectively. They both allow visiting mobile agents to be forwarded to and execute on any node performing a service agent, not necessarily the primary agent. Especially, in case of the protocol for deterministic services, after a backup service agent has received a mobile agent request and obtained the delivery sequence number of the request from the primary service agent, the backup agent, not the primary one, is responsible for processing the request and coordinating with the other replica service agents.

1 Introduction

Mobile agent paradigm is considered as a promising vehicle for developing distributed computing systems such as grid computing, e-commerce, active networks and embedded systems because it provides a number of advantages such as reduction of network traffic and asynchronous interaction and so on unlike the traditional client server paradigm [1, 5, 7]. As the mobile agent system is gaining popularity and the number of mobile agent's users rapidly increases, a large number of mobile agents may concurrently be transferred to a node supporting a particular service. In this case, the service agent on the node can be a performance bottleneck and if the agent fails, the execution of all the transferred mobile agents be blocked. In order to solve these problems, the service agent function should be replicated at multiple nodes. This approach may balance the load caused by the mobile agents and even if some service agents crash, continuously allow the other service agents to provide the mobile agents with the

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service. There are two approaches used in distributed systems to potentially be applied for satisfying the goal: active and passive replication [8]. Among the two approaches, the passive replication approach [3, 4] has three desirable features we focus on. First, the approach enables its consistency to be guaranteed even if replicated service agents are performed in a non-deterministic manner. Thus, it can be applied to every replicated service regardless of the execution behavior of the service. Second, it needs lower processing power during failure-free execution than the active replication one. Third, mobile agents has only to use a unicast primitive, not a multicast one because they send service requests only to the primary service agent. But, the traditional passive replication approach may result in some scalability and performance problems when being applied to the mobile agent system as a fault-tolerant technique for replicated services. In other words, to the best of our knowledge, previous works [3, 4] uniformly applied the traditional passive replication approach to each replicated service regardless of whether it is deterministic or non-deterministic. But, in this approach, every mobile agent request should be sent only to the primary service agent, which processes the request and coordinates with the other live replicas and then returns a response of the request to the mobile agent. This special role of the primary is necessarily required to ensure the consistency for non-deterministic services. Moreover, the traditional passive replication approach forces all visiting mobile agents to be transferred to and execute their works in order only on the node running the primary service agent of each domain. These inherent features may cause the extreme load condition to occur on the primary service agent when a large number of mobile agents are forwarded to the service domain and access its resources. Thus, this previous strategy may not achieve high scalability and performance. This paper presents a scalable strategy to apply an appropriate passive replication protocol to each service according to its execution behavior because deterministic services require weaker constraints to ensure their consistency than non-deterministic ones. For this goal, two passive replication protocols are designed in this paper. The first protocol for non-deterministic services is named *PRPNS* and the second protocol for deterministic services, *PRPDS*. They both allow visiting mobile agents to be forwarded to and execute on any node performing a service agent, not necessarily the primary agent. Especially, in case of the second protocol *PRPDS*, after a backup service agent has received a mobile agent request and obtained the delivery sequence number of the request from the primary service agent, the backup agent, not the primary one, is responsible for processing the request and coordinating with the other replica service agents. Due to this feature, *PRPDS* is more lightweight than *PRPNS* tolerating non-deterministic servers such as multi-threaded servers.

2 The Proposed Passive Replication Protocols

In here, we attempt to improve scalability of mobile agent systems by using the appropriate passive replication protocol for each replicated service domain

according to whether the service is deterministic or non-deterministic. For this purpose, two passive replication protocols *PRPNS* and *PRPDS* are introduced.

When mobile agents are concurrently transferred to a non-deterministic replicated service, the consistency is ensured by applying the traditional passive replication protocol. When mobile agent a_j attempts to use the service of a non-deterministic replicated service domain u_i , a_j should be transferred from its current node to the node where the primary service agent of u_i , u_i^{prim} , executes. Then, the following phases are performed:

(Phase 1). When u_i^{prim} receives a request message from mobile agent a_j , u_i^{prim} processes the message. After the execution, it generates $(response, psn, next_state)$, where $response$ is the response of the message, psn identifies the processed request message and $next_state$ is the state of u_i^{prim} updated by processing the request.

(Phase 2). u_i^{prim} sends all backup service agents the update message $(response, psn, next_state, j, reqid)$ using **View Synchronous Multicast (VSCAST)** [8] respectively, where j identifies a_j and $reqid$ is the send sequence number of the request message. In here, *VSCAST* is the multicast communication primitive used to ensure correctness of the passive replication approach. When each backup service agent receives the update message, it updates its state using $next_state$, maintains $(response, j, reqid)$ in its buffer and then sends an acknowledgement message to u_i^{prim} . In this case, $(response, j, reqid)$ is needed to ensure the exactly once semantics despite u_i^{prim} 's failure.

(Phase 3). After receiving an acknowledgement message from every live backup service agent, u_i^{prim} sends $response$ to a_j .

Therefore, this protocol forces all visiting mobile agents to be transferred to and execute their works in order only on the node running the primary service agent of each domain. This behavior may cause the extreme load condition to occur when a large number of mobile agents are forwarded to the service domain to use the non-deterministic service. For example, in figure 1, three mobile agents a_t^l , a_s^m and a_r^n are concurrently transferred to the node $node_i^2$ where the primary service agent of u_i , u_i^2 , is running. The mobile agents perform the service of u_i in order via only u_i^2 using the above mentioned protocol respectively. Thus, we introduce a passive replication protocol for non-deterministic service, *PRPNS*, to solve the problem by allowing mobile agents to be forwarded to and execute on each a node performing a service agent, not necessarily the primary agent. The protocol forces each service agent p to forward every request received from mobile agents to the primary service agent. Afterwards, the primary agent performs the phases 1 through 2 previously mentioned to satisfy the consistency condition for non-deterministic service. After receiving an acknowledgement from every normal backup service agent, the primary agent sends the response of the request to the service agent p , which forwards it to the corresponding mobile agent.

Fig. 1. an execution of three mobile agents accessing a replicated service u_i in the traditional passive replication protocol

Fig. 2. an execution of three mobile agents accessing a replicated service u_i in the protocol *PRPNS*

Figure 2 illustrates how the protocol *PRPNS* executes. In this figure, mobile agents a_t^l , a_s^m and a_r^n are transferred to and execute on the nodes $node_i^2$, $node_i^1$ and $node_i^0$ for accessing service u_i . Then, the mobile agents perform their tasks via u_i^2 , u_i^1 and u_i^0 respectively. For example, if u_i^1 receives a request from a_s^m , it forwards the request to the primary service agent u_i^2 . Afterwards, u_i^2 processes the request and coordinates with the other service agents u_i^1 and u_i^0 using *VSCAST*. When receiving acknowledgements from the two backup service agents, it sends the response of the request to u_i^1 , which forwards the response to a_s^m . From this example, we can see that *PRPNS* improves scalability of replicated services in case a large number of mobile agents attempt to use a particular service simultaneously. If a mobile agent accesses a service via a backup service agent in this protocol, two more messages are required per request compared

with the traditional protocol. However, the additional message cost is not significant because each service domain is generally configured on a local area network like Ethernet.

A deterministic replicated service requires weaker constraints to ensure the consistency than a non-deterministic one. In other words, after the primary service agent has determined the processing order of every request from mobile agents, it is not necessary that only the primary agent handles all requests, and coordinates with the other replica service agents like in the protocol *PRPNS*. With this observation, we attempt to use a lightweight passive replication protocol, *PRPDS*, for each deterministic service domain. The proposed protocol has the following features.

- Each mobile agent can use a service via the primary service agent or a backup one.
- Only the primary service agent determines the processing order of every request from mobile agents.
- After a backup service agent has received a mobile agent request and obtained the order of the request from the primary service agent, the backup agent, not the primary one, processes the request and coordinates with the other replica service agents including the primary agent.

Due to these desirable features, this protocol enables each visiting mobile agent to be forwarded to and execute on a node running any among replicated service agents in the service domain. If mobile agent a_j is transferred to the node where a backup service agent u_i^{backup} executes, *PRPDS* executes the following phases. Otherwise, the three phases of *PRPNS* are performed.

(Phase 1). When u_i^{backup} receives a request message from a_j , u_i^{backup} asks the primary service agent u_i^{prim} the *psn* of the request message. In this case, after u_i^{prim} determines the *psn* of the message, it notifies u_i^{backup} of the *psn*. Then, u_i^{prim} processes the request message and saves $(response, psn, next_state, j, reqid)$ of the message in its buffer. When receiving the *psn*, u_i^{backup} processes the corresponding request and generates $(response, psn, next_state)$ of the request.

(Phase 2). u_i^{backup} sends the other service agents the update message $(response, psn, next_state, j, reqid)$ using *VSCAST* respectively. When each service agent except for u_i^{prim} receives the update message, it updates its state using *next_state*, maintains $(response, j, reqid)$ in its buffer and then sends an acknowledgement message to u_i^{backup} . If u_i^{prim} receives the update message from u_i^{backup} , it just removes the element $(response, psn, next_state, j, reqid)$ for the message from its buffer, saves $(response, j, reqid)$ in the buffer and sends an acknowledgement message to u_i^{backup} .

(Phase 3). Once u_i^{backup} receives an acknowledgement message from every other live service agent, it sends *response* to a_j .

Figure 3 shows an execution of three mobile agents a_t^l , a_s^m and a_r^n attempting to use service u_i via u_i^2 , u_i^1 and u_i^0 in the protocol *PRPDS*. In this figure, only the

Fig. 3. an execution of three mobile agents accessing a replicated service u_i in the protocol $PRPDS$

procedure is pictured to execute in $PRPDS$ when a_s^m sends a request to u_i^1 . In this case, u_i^1 asks the primary agent u_i^2 the *psn* of the request. u_i^2 determines the *psn* and sends it to u_i^1 . Then, u_i^2 processes the request and saves (*response*, *psn*, *next_state*, $j + 1$, *reqid*) of the request in its buffer. Meanwhile, after obtaining the *psn* of the request from the primary agent, u_i^1 processes the request and coordinates with the other service agents u_i^2 and u_i^0 using $VSCAST$ to satisfy the consistency condition for deterministic service. When u_i^1 receives an acknowledgement from every live agent, it sends the response to a_s^m . From this figure, we can see that the protocol $PRPDS$ may significantly improve scalability of replicated services by enabling each visiting mobile agent to use a particular service via any among replicated service agents on the service domain and the request processing and coordination load to be distributed between a set of service agents.

2.1 Recovery

If service agents fail on a service domain, the proposed two protocols, $PRPNS$ and $PRPDS$, should perform their recovery procedures to satisfy each consistency condition for nondeterministic service or deterministic service despite the failures respectively. Firstly, in case of the crash of the primary service agent u_i^{prim} , the two protocols execute both each appropriate recovery procedure in the following cases.

(Case 1). The primary service agent u_i^{prim} fails before finishing the phase 1.

In this case, a new primary service agent $u_i^{prim'}$ is elected among all backup service ones. Since no response of each request can be received from u_i^{prim} , the request will be resent to $u_i^{prim'}$, which has only to perform the phases 1 through 3.

(Case 2). The primary service agent u_i^{prim} fails after completing the phase 1, but before sending the response to the corresponding mobile agent.

Like in case 1, a new primary agent $u_i^{prim'}$ is selected. To ensure linearizability in this case, either all the backup service agents receive the update message, or none of them receive it. *VSCAST* is used to satisfy the atomicity condition of linearizability in case of an asynchronous mobile agent system with an unreliable failure detector. If no backup service agent receives the update message, this case is similar to case 1. Otherwise, $(response, j, reqid)$ in the phase 2 is used to ensure the exactly-once semantics. In other words, when the request from the corresponding mobile agent is sent to the new primary service agent $u_i^{prim'}$ again, the latter immediately sends the response of the request to the first without handling the request.

(Case 3). The primary service agent u_i^{prim} fails after finishing the phase 3. Like in case 1, a new primary service agent $u_i^{prim'}$ is selected and identified.

Secondly, when a backup service agent u_i^{backup} crashes, *PRPNS* and *PRPDS* perform their recovery procedures as follows. In *PRPNS*, u_i^{backup} is just removed from its service group. On the other hand, *PRPDS* executes a corresponding recovery procedure in each following case.

(Case 1). Backup service agent u_i^{backup} fails before asking the primary service agent u_i^{prim} the *psn* of each request in the phase 1.

In this case, u_i^{backup} is just removed from its group. Afterwards, u_i^{backup} 's failure is detected because of no response of the request from it.

(Case 2). Backup service agent u_i^{backup} fails before finishing the phase 1.

(Case 2.1). The primary u_i^{prim} fails.

The other backup service agents select a new primary service agent, $u_i^{prim'}$, among them.

(Case 2.2). The primary u_i^{prim} is alive.

Detecting u_i^{backup} 's crash, u_i^{prim} retrieves every update information, which is form of $(response, psn, next_state, j, reqid)$, from its buffer and sends it to the other live backup service agents respectively. In this case, *VSCAST* is used to ensure linearizability.

(Case 3). Backup service agent u_i^{backup} fails after sending the update message to the other service agents in the phase 2, but before sending the response to the corresponding mobile agent.

As u_i^{backup} sent the update message to the other service agents by using *VSCAST*, the entire consistency is ensured. Therefore, the service group of u_i^{backup} has only to remove u_i^{backup} .

(Case 4). Backup service agent u_i^{backup} fails after completing the phase 3. u_i^{backup} is removed from its group and mobile agents can detect that u_i^{backup} fails.

3 Conclusion

This paper proposed a new strategy to improve scalability of mobile agent systems by applying an appropriate passive replication protocol to each replicated service according to its execution behavior, deterministic or non-deterministic. For this purpose, we presented the two passive replication protocols, *PRPNS* and *PRPDS*, for non-deterministic and deterministic services respectively. While ensuring linearizability [6], they both allow visiting mobile agents to be forwarded to and execute their tasks on any node performing a service agent, not necessarily the primary agent. Especially, the more lightweight protocol *PRPDS* allows any service agent to process each mobile agent request and coordinate with the other replica service agents after receiving the request and obtaining its delivery sequence number from the primary agent. Thus, if *PRPDS* is well-combined with existing load balancing schemes [2], the request processing and coordination load can be evenly distributed among a set of deterministic and replicated service agents based on the workload of each service agent.

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