國 立 清 華 大 學

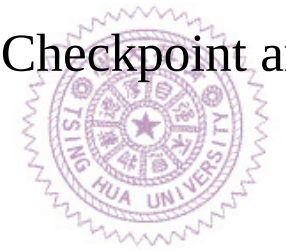
資訊工程研究所

碩士論文

使用中斷點和回復機制

實現容器叢集中的遷移和高可用性

Container Migration and High Availability in Docker Swarm using Checkpoint and Restoration



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中華民國一零五年七月

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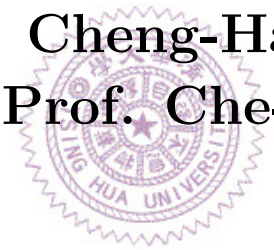

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July 2016

中文摘要

容器技術自 2013 年 Docker 發表後在全世界迅速竄紅，Container 解決了維護人員在伺服器進行大量部屬時的痛點，使得環境部屬只需要建立完容器映像檔後就可以進行大量部屬，並對每一個容器環境進行隔離。

在這篇論文中，我們提出了在 Docker swarm 叢集中，將容器在多個節點中相互搬移。另外，可以針對特定的容器定期設定 checkpoint 儲存至雲端儲存空間，若叢集中的節點遇到不正常的離線時，可以及時回復最近的容器狀態到健康的節點上。

Abstract

Container becomes a popular technology since Docker has published in 2013. Container technology has solved programmer and system maintainer when they have to deploy their applications in the servers. They just need to build the container images, and the container images can run on everywhere they want. Container technology also isolates each container environments just likes a single host machine.

In this paper, we not only migrate the Docker containers between two physical machines, but also migrate the Docker containers in the Docker Swarm cluster. Furthermore, we enhance the high availability in the Docker Swarm cluster, the container can be set that checkpoint the container images to remote storage service; whenever the Docker Nodes are fail, the containers which run in the failed Docker Nodes will restore the newest checkpoint to the alive Docker Nodes as well.

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Chapter 1

Introduction

Nowadays, cloud computing [4] has been used widely. People would like to use a lot of normal computers and gather them into a cluster. An increasing number of companies build their data centres or use cloud platforms to construct their business application. However, the more computers we have, the larger of a power consumption problem we have to solve. At the same time, to make sure every computers' process in the cluster are alive, high availability [8, 12] becomes a more important role in cloud computing.

Virtualization is a popular technology that is used wildly in cloud computing, including virtual operating systems [15, 20], computer hardware platforms, storage devices [17] and computer network resources [7]. Virtual Machine [11] is a technology to emulate a particular computer like a real computer. It can partition the physical machine's resources, such as CPU, memory, storage, and network. A hypervisor [21, 10] uses execution to manage and share the host physical machine hardware, it allows many different Virtual Machines to be isolated from each other.

Container [18] is an operating system level virtualization which runs as an isolated process in userspace on the host operating system and shares the same operation system kernel with other containers. It provides kernel namespace [6] such as PID, IPC, network, mount, and user namespace to isolate each container environment from the host operation system. In order to control hardware resource such as CPU, memory, network, and disk I/O, container uses cgroups to limit each of the containers resources. Container doesn't have hypervisor to isolate from the host operating system, therefore, it can offer better performance than Virtual Machine

[19, 9]. There are already many software to control container, such as LXC [13], LXD, Open VZ, etc. For now, Docker [2] is the most popular container engine. The Virtual Machine and Container architecture is shown as Figure 1.1.

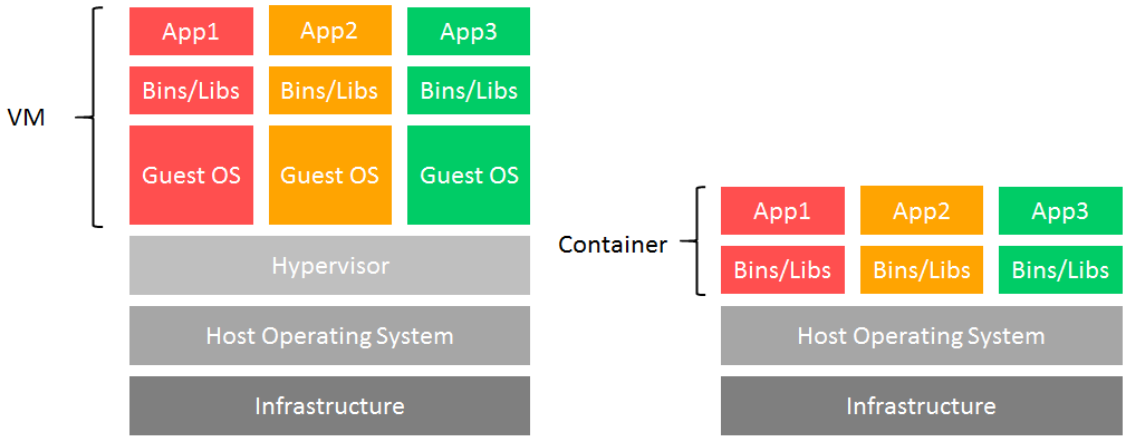


Figure 1.1: Virtual Machine and Container architecture

Checkpoint and restoration [5] can freeze a running process state and save process information to checkpoint images. It can be used to checkpoint image files to restore the process state. These features can be used to checkpoint and restore containers because each container is a process in the host operating system.

In this paper, we choose container but not Virtual Machine to do migration between two host machines, because container need less disk storage and less network transport resources. We not only use checkpoint and restoration to migrate the containers between two physical computers but also migrate the containers in the Docker Swarm cluster. Moreover, we improve high availability and rescheduling feature in Docker Swarm using checkpoint and restoration than keep versions of container checkpoint images in the remote storage server that whenever the computer fails, Docker Swarm manager will restore the containers from the checkpoint images. In some cases, we use pre-dump and track-memory to save about 10% 20% container checkpoint frozen time and at least 200% storage space.

Chapter 2

Background

2.1 Docker

Docker [2] is an open-source project container engine. It provides an additional layer of abstraction and automation of operating-system-level virtualization in Linux. Moreover, Docker has extra image management and layered file system to optimize the performance of container and reduce disk space. Docker images and Docker containers share the same image layer file if they have the same data. When Docker creates container, Docker will create a writable layer that allow the container application to change file system. Docker has two parts; Docker Client and Docker Daemon.

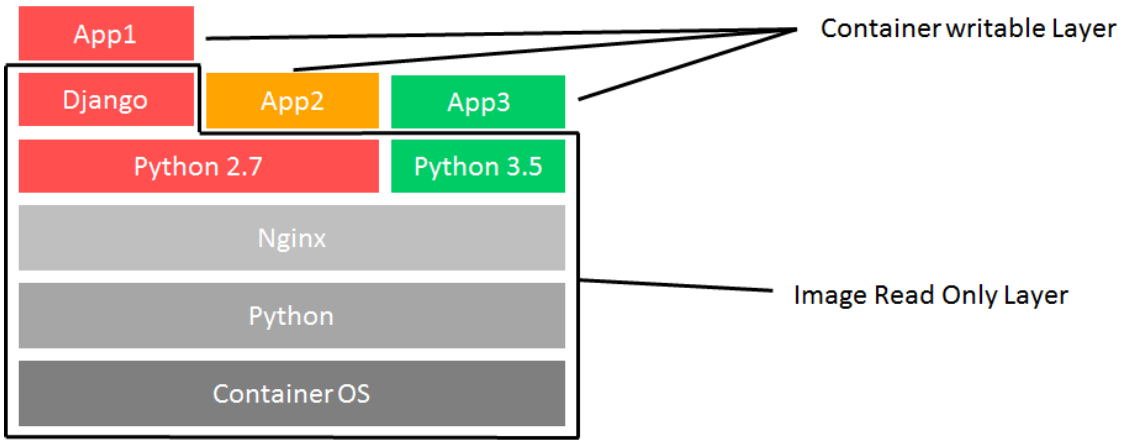


Figure 2.1: Docker layered file system

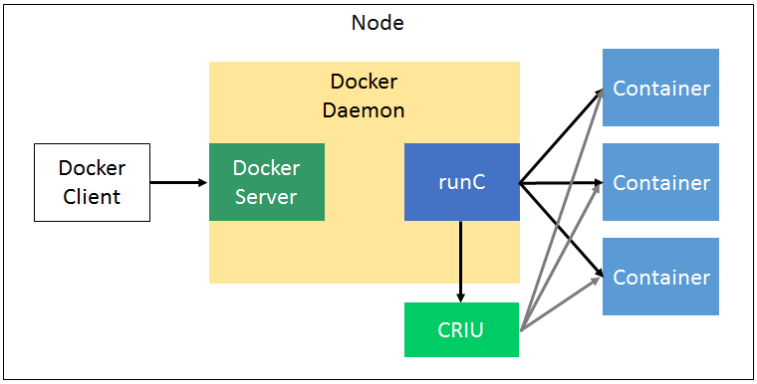


Figure 2.2: Single node Docker

2.1.1 Docker Client

Docker is typical client/server architecture application. Docker Client is a CLI (Client Line Interface) in Docker. Docker uses Docker Client to send and receive requests to Docker Daemon. Also, Docker supports remote RESTful API to send and receive HTTP requests to Docker Daemon. In additional, it has been implemented by more than 10 programming languages.

2.1.2 Docker Daemon

Docker Daemon is a daemon that runs as system service. It has three of the most importance features:

- Receive and handle requests from Docker Clients.
- Manage containers.
- Manage container images.

When Docker Daemon is running, it will run a server that receives requests from Docker Clients or remote RESTful API. After receiving requests, server will pass the requests by router to find the handler to handle the requests. By default, Docker Daemon listens to UNIX socket requests, it serves root permission, or docker group membership. Whenever user wants Docker Daemon to listen to remote RESTful API or Docker Swarm requests, it has to enable the TCP socket.

2.1.3 runC

When Docker came into being, Docker used LXC as its container execution environment. After Docker version 0.9, Docker dropped LXC but used libcontainer as its default execution environment. runC is basically a repackaging of libcontainer, which is a CLI tool for running containers according to the OCI(Open Container Initiative) specification. It doesn't need any dependency from the operating system, it can control the Linux Kernel, including namespace, cgroups, apparmor, network, capabilities, firewall, etc. runC provides a standard interface to support the containers management that Docker can use it to control the containers.

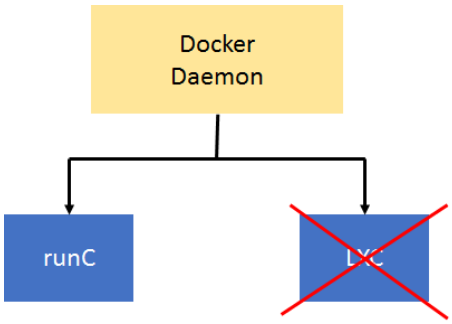


Figure 2.3: Docker Daemon execution environment with runC and LXC

2.2 CRIU

CRIU [1] (Checkpoint/Restore in Userspace) stands for Checkpoint and Restore in User Space, creates a complete snapshot of the state of a process, including things like memory contents, file descriptors, and even open TCP connections. It can be used for suspending and resuming processes, or migrating them from one machine to another.

2.3 Docker Swarm

There are many Docker cluster software, like Docker Swarm, Google Kubernetes, Apache Mesos, etc. We choose Docker Swarm because it supports native Docker API, and Docker usage. We don't need to learn the other Docker cluster software.

Docker Swarm [3] is a native clustering for Docker. It gathers several Docker engines together into one virtual Docker engine. Docker Swarm serves standard Docker API, so it can be connected by Dokku, Docker Machine, Docker Compose, Jenkins, DockerUI, Drone, etc. Of course, it also supports Docker Client as well.

In Docker Swarm, it has two components which are Swarm Manager and Swarm Node. Swarm Manager is the manager which handles Docker Client and RESTful API requests and manages multiple Docker Nodes' resources. Docker Node is an agent which sends heartbeat to Discovery Service to ensure Docker Daemon is alive in the cluster.

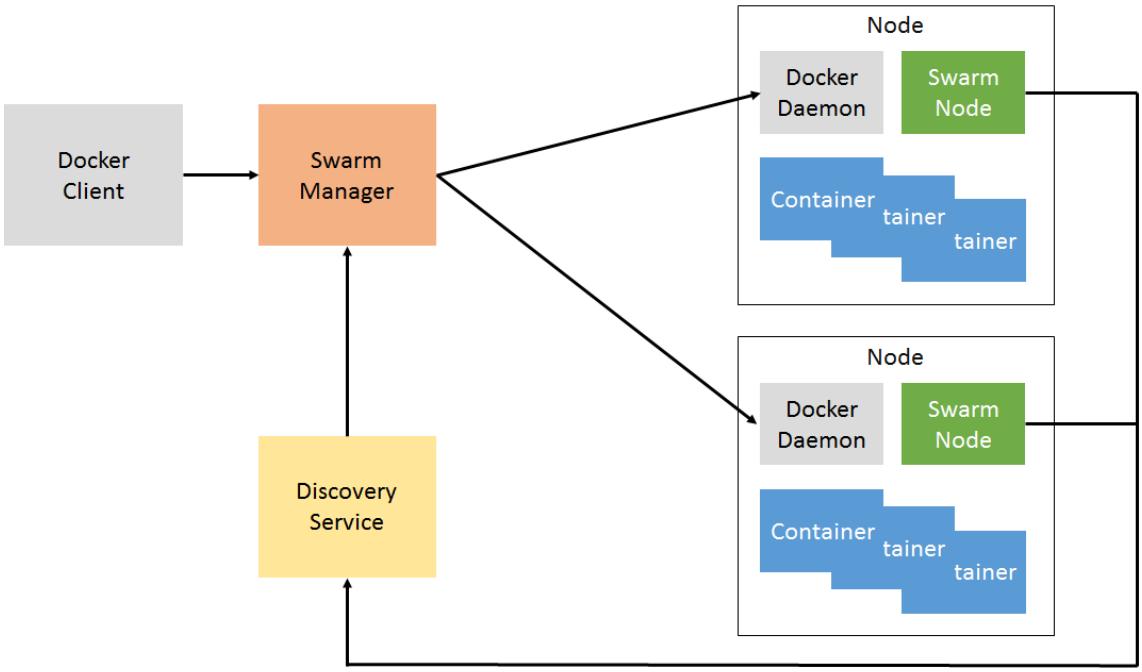


Figure 2.4: Docker Swarm architecture

2.3.1 Discovery services

Docker Swarm provides multiple Discovery Services backends. They are used to discover the nodes in the cluster. There are:

- Using a distributed key/value store, like Consul, Etcd and Zookeeper.
- A static file or list of nodes.
- Docker Hub as a hosted discovery service.

Otherwise, it also supports any modules that satisfy Discovery API interface.

2.3.2 Scheduler

Docker Swarm scheduler decides which nodes to use when creating and running a container. It has two steps: First, the scheduler follows user's filters to decide which nodes conform to it. Secondly, it undergoes multiple strategies to select the best node in the cluster.

Filter

Filters are divided into two categories; Container configuration filters operate on characteristics of containers, or on the availability of images on a host. Node filters operate on characteristics of the Docker host or on the configuration of the Docker Daemon.

The container configuration filters are:

- Affinity
- Dependency
- Port filter

The node filters are:

- Constraint
- Container slots
- Health filter

Strategies

The Docker Swarm scheduler features multiple strategies for ranking nodes. Docker Swarm currently supports these values:

- Spread
- Binpack
- Random

Spread and Binpack strategies compute rank according to a nodes available CPU, its RAM, and the number of containers it has. It selects a node at random. Under the Spread strategy, Swarm chooses the node with the least number of containers. The Binpack strategy chooses the node which has executed most containers. The Random strategy uses no computation and chooses nodes at random regardless of their available CPU or RAM.

2.3.3 High availability of Swarm Manager

In Docker Swarm, Swarm Manager responds to the cluster and manages the resources of multiple Docker Nodes at scale. If Swarm Manager dies, we have to create a new one and deal with the interruption of service.

The High availability feature allows Docker Swarm has multiple Swarm Manager instances. We can create a primary manager and multiple replica instances. Whenever we send requests to replica instances, it will be automatically proxied to the primary manager. In addition, if the primary manager fails, the other replica instances will lead a new primary manager.

2.3.4 High availability of Docker Swarm containers

In Docker Swarm, it has a rescheduling policy. As we set the reschedule policy when we start a container, whenever Swarm nodes fail, Swarm Manager will restart all of the containers to another alive Swarm Nodes.

Chapter 3

Design and Implementation

3.1 Docker

Native Docker has two parts, Docker Client and Docker Daemon. Docker Daemon has several components include server, engine, registry, graph, driver and runC. To support Checkpoint and Restoration request, some of these steps should be implemented.

3.1.1 Docker Client

There are 3 Docker commands implementation in Docker Client, including Checkpoint, Restore, and Migrate. In Checkpoint command should have these configurations:

- Image directory - Dump checkpoint image directory.
- Work directory - Dump checkpoint image log directory.
- Leave running - After dumping the checkpoint images, consideration is required whether the container keep running.
- Pre-dump - Pre-dump checkpoint memory image to minimize frozen time.
- Pre image directory - Define which version image to compare.
- Track memory - Track memory to pre image directory image to minimize disk space.

In Restore command, it should have these configurations:

- Image directory - Checkpoint image directory to restore from.
- Work directory - Directory for restore log.
- Force - Force restoring the container from image directory whether container is running.

In Migrate command, it focuses on Docker Swarm Scheduler filter configurations. Meanwhile, in Run command, it is possible for the container to set filter configurations with environment variables or labels. Therefore, the implementation of environment variables and labels in Migrate command is required.

3.1.2 Docker Daemon

In native Docker Daemon, it does not support Checkpoint and Restore commands. Fortunately, it is already implemented in runC, so we have to add a proxy between Docker Daemon and runC, which can handle Docker Client's Checkpoint and Restore requests.

3.2 Docker Swarm Configuration

As Figure 3.1, it shows a remote storage server for saving Docker containers dump checkpoint images and it should have fault tolerant to avoid service shutdown.

3.3 Docker Containers Migration in Docker Swarm

Docker Swarm creates containers through Swarm scheduler to dispatch Docker nodes. If a specific node needs to be assigned to create a container, filters such as Constraint, Affinity or Dependency should be set. In migrating a container in Docker Swarm, a Constraint should be assigned in order to avoid the container to migrate to the same node.

Step 1. Check Docker Swarm cluster has at least two Swarm nodes.

Step 2. Parse Docker Client requests to analyse label and environment variables, and transform label and environment variables to Docker Swarm filters.

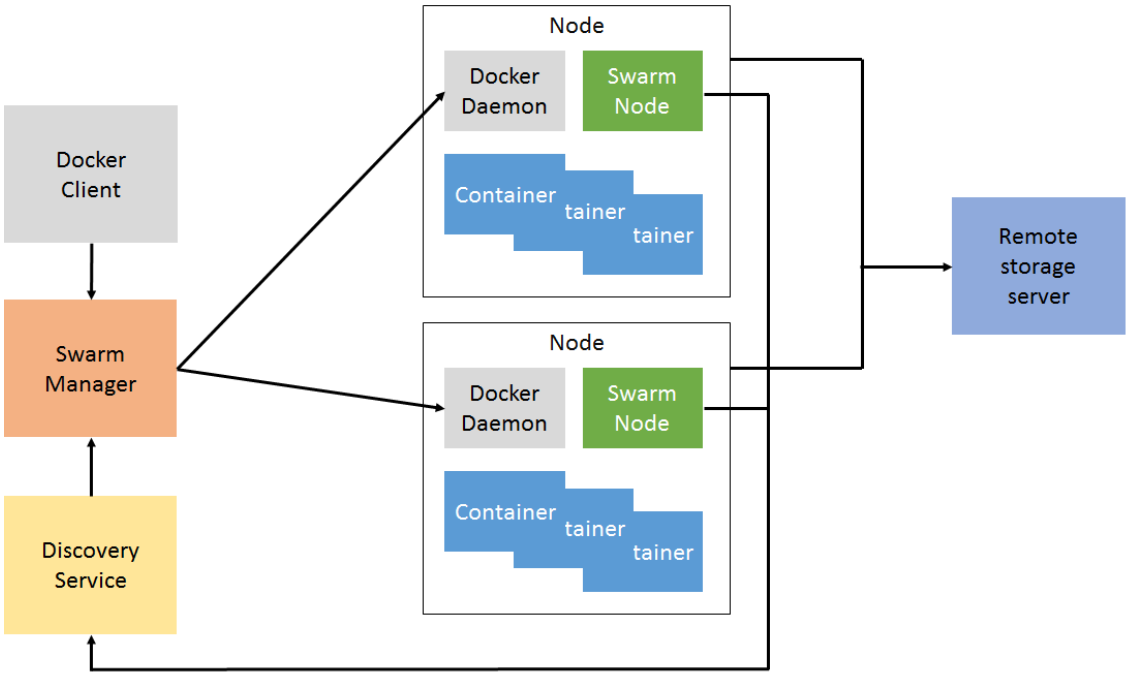


Figure 3.1: Docker Swarm with remote storage server

Step 3. Constraint filter should be added to make sure the container will not be migrated to the same node.

Step 4. Create empty container on the Docker Swarm scheduler which node its pointing to, this could lead to downloading the container image if it doesn't exist in the be chosen node.

Step 5. Pre-dump the container's checkpoint images which we want to migrate to decrease container's frozen time.

Step 6. Dump the container's checkpoint images by tracking memory from the pre-dumped checkpoint images.

Step 7. Restore the container's checkpoint images to the empty container that Docker Swarm scheduler points to.

Step 8. Delete the checkpoint images.

Step 9. If the container has been migrated which has set the Checkpoint and Restoration Rescheduling Policy, it will restart the Checkpoint and Restoration Rescheduling Policy 3.4.

3.4 Docker Swarm Checkpoint and Restoration Rescheduling Policy

In Docker Swarm, it has Rescheduling Policy. As the reschedule policy is set when we start a container, whenever Swarm nodes fail, Swarm Manager will restart the containers to another alive Swarm Nodes.

To improve this policy, a Checkpoint Ticker should be needed to keep every containers' checkpoints up to date. Whenever Swarm Nodes fail, Swarm Manager will restore the containers which their checkpoints has been dumped by Swarm Manager to the remote storage server. Otherwise, the Checkpoint Ticker provides the version of checkpoint image by tracking memory. It only dumps the different memory pages' checkpoint to new version checkpoint images.

In addition, Docker Swarm Checkpoint and Restoration Rescheduling Policy also supports high availability whenever Docker Swarm primary manager fails, the others Swarm Manager replica instances will lead to a new primary manager. After replica has chosen a new primary manager, it will restart the container's Checkpoint Tickers. By experiment, it can save at least 2 times storage space.

3.4.1 Docker Swarm Container Checkpoint Ticker

Algorithm 1 shows the Container Checkpoint Ticker's algorithm. In line 1 and 2, checkpoint-time period T_i and version-group VG_i are set when the container C_i is created through Docker Swarm Manager, and every T_i is independent. Each T_i in the Docker Swarm cluster has its starting time and time ticker, time ticker will dump checkpoint image repetitively at regular intervals. If version-group VG_i has not been set, it will be set to 5. Checkpoint version $V_i = 0$ and pre-dump checkpoint version $pre\text{-}dumpV_i = 0$ should be defined for each container C_i.

In line 4 to 18, for each container is running and C_i checkpoint ticker period T_i pounds, C_i, Swarm Manger will do line 5 to 17. In line 6 to 9, if the container C_i does not has any pre-dump image or newest version-group VG_i checkpoint is full, Swarm Manger will send the request to Swarm Node N_i to create a new directory and pre-dump the checkpoint image as pre-dump version $pre\text{-}dumpV_i$. After pre-dumping the container checkpoint image or C_i has previous version checkpoint images, Swarm

Manager will send requests to dump checkpoint image to Swarm Node N_i to dump checkpoint version V_i. Whenever dumping checkpoint image, CRIU will track the memory difference to the previous checkpoint images or the pre-dumping checkpoint images to reduce image disk space usage. As it is shown as Figure 3.2, every container has each pre-dump checkpoint directories and each pre-dump checkpoint directories have version-group versions checkpoint images. In line 10 to 12, Swarm Manager sends delete checkpoint request to N_i to delete oldest Pre-dump version directory whenever container has more than three Pre-dump versions directory.

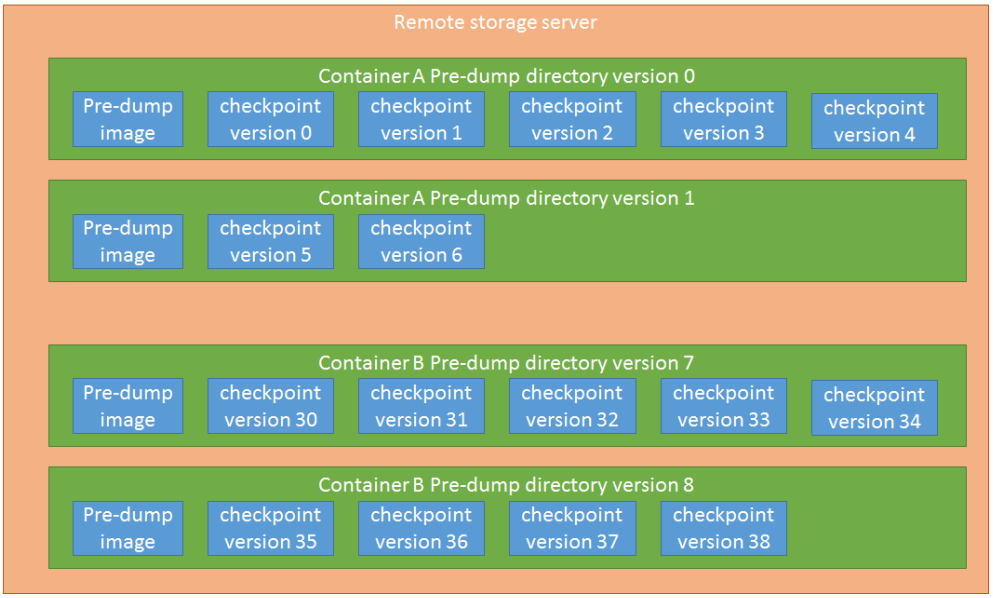


Figure 3.2: Containers checkpoint versions in remote storage server

3.4.2 Docker Swarm Restore Rescheduling Policy

Algorithm 2 gives a specific explanation of Restore Rescheduling Policy. In line1, R_i label is set when the container C_i is created by Docker Swarm Manager. In line 3 to 7, whenever Swarm Nodes N_i fail, Swarm Manager will execute procedure RESTORE CONTAINER that restores every container C_i which has R_i label to another Swarm Nodes N_i.

In line 9 to 21, each container C_i executes procedure RESTORE CONTAINER; Swarm Manager will choose a Swarm Node N_r and create an empty container C_r in N_r. In this step, Swarm Manager will check whether N_r has the container's image.

Algorithm 1 Checkpoint Ticker Algorithm

Input: The set of Swarm Nodes: $\{N_1, N_2, ..., N_m\}$; The set of containers: $\{C_1, C_2, ..., C_n\}$; Version-group: VG_i; Checkpoint-ticker period: T_i;

Output: pre-dump images $pre\text{-}dumpV_i$; dump images V_i ;

```
1: Set T_i and VG_i labels when create the container C_i;
2: initial V_i = 0, pre-dumpV_i = 0;
3:
4: for each C_i in N_i do
5:     while C_i running & T_i pounding do
6:         if version % VG_i == 0 then
7:             pre-dump checkpoint image pre-dumpV_i;
8:         end if
9:         dump checkpoint image V_i;
10:        if VG_i directory > 3 then
11:            delete oldest pre-dump checkpoint pre-dumpV_i directory;
12:        end if
13:        V_i = V_i + 1;
14:        if V_i % VG_i == 0 then
15:            pre-dumpV_i = pre-dumpV_i + 1;
16:        end if
17:    end while
18: end for
```

If N_r doesn't have the container's image, N_r will download the container's image from Docker remote registry and create the empty container C_r. As result of creating container C_r, Swarm Manager restores the fail container C_i checkpoint image to C_r. To avoid a fail restoration, Swarm Manager will retry to restore the second last version's checkpoint, and it will retry version-group VG_i (default is 5) for several instances. The container C_i checkpoint image will be removed after restoring the container C_i.

Whenever Swarm Manager's attempts to retry are all failed for VG_i times, it will create and restart a new container as normal Docker Swarm Rescheduling Policy.

3.4.3 High Availability of Swarm Manager in Docker Swarm Checkpoint and Restore Rescheduling Policy

Whenever Docker Swarm primary manager fails, the others Swarm Manager replica instances will lead a new primary manager. After replica leading a new primary manager, it searches every Docker Node's containers which has Checkpoint and Restore Rescheduling Policy's label. If the containers have Checkpoint and Restore Rescheduling Policy's labels, Docker Swarm new primary manager will restart container checkpoint tickers.

Algorithm 2 Restore Rescheduling Algorithm

Input: The set of Swarm Nodes: $\{N_1, N_2, ..., N_m\}$; The set of containers: $\{C_1, C_2, ..., C_n\}$; Version-group: VG_i; Checkpoint-ticker period: T_i; Restore rescheduling policy label:R_i;

Output: Restored containers:C_{ri};

Set R_i labels create the container;

if N_i fail **then**
    for all C_i in fail N_i has R_i **do**
        RESTORE CONTAINER;
    end for
end if

procedure RESTORE CONTAINER
    N_r ⟵Create a empty container C_r
    for V_i downto V_i - VG_i **do**
        C_{ri} ⟵ Restore checkpoint V_i;
        if Restore C_{ri} success **then**
            break
        end if
    end for
    Delete the container checkpoint image;
    if Restore container C_i fail **then**
        C_r ⟵ Restart the container; C_i;
    end if
end procedure

Chapter 4

Experiments

4.1 Environment

We developed our experiments environment cluster were listed as table 4.1, and created 4 virtual machines in the computer that each of their resource were listed as table 4.2. We will mount NFS to each virtual machines and test 2 types each of NFS, hard disk, and memory(tmpfs). In addition, we will test the difference between **Direct** method that is defined as new checkpoint image and **Track-memory** method that is defined as pre-dump checkpoint image which is followed by checkpoint images.

CPU	Intel Xeon(R) CPU-E5-2630 v3 @ 2.40GHz x 32
Memory	64 GB
Disk	1.0 TB
OS	Ubuntu 15.10 64 bit
Kernel version	4.4.4-040404-generic
Docker version	1.10.3
Docker Swarm version	1.2
Virtual Box version	5.10.14

Table 4.1: Experiment environment

CPU	Intel Xeon(R) CPU-E5-2630 v3 @ 2.40GHz x 4
Memory	8 GB
Disk	40 GB
OS	Ubuntu 15.10 64 bit
Kernel version	4.4.4-040404-generic
Docker version	1.10.3
Docker Swarm version	1.2

Table 4.2: Virtual Machine experiment environment

4.2 Container Migration Time

As shown in Figure **??**, native is a based line of the other kinds of experiment. We choose Redis[16] as our migration container, because it uses memory to save its data. Therefore, we can check the correctness of Redis data to make sure container migration is success.

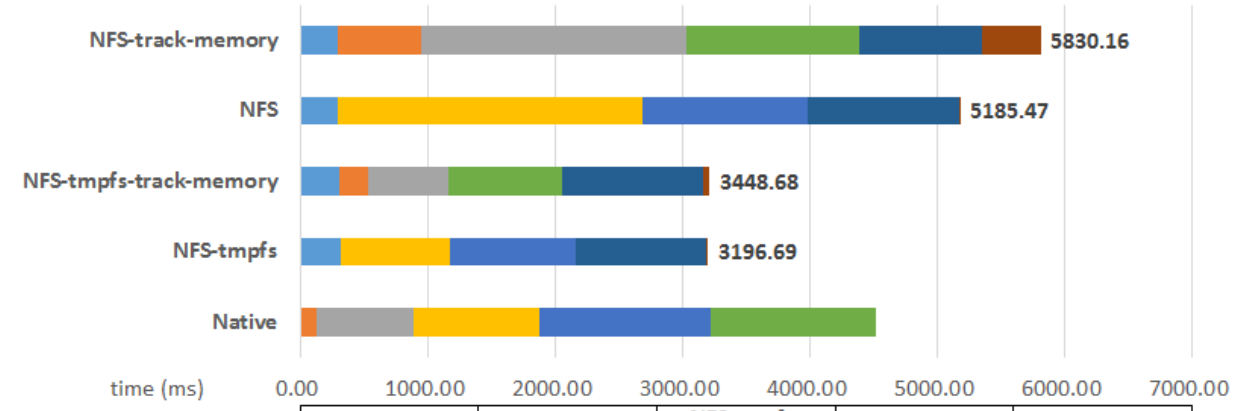
In the beginning, creating the container on another Swarm Nodes is fast for all environments because we assume that they have downloaded their container images from the remote repository, thus, they do not need to transport container images from the other Swarm Nodes.

Next, in **Track-memory** method, the container has to pre-dump the checkpoint image at the version-group created. After pre-dumping the checkpoint image, dumping checkpoint will track memory different with the pre-dump checkpoint image. On the other hand, **Track-memory** method, checkpoint ticker dumps the checkpoint image directly. The result of total checkpoint time, **Track-memory** method is longer than the other one, because it has to add pre-dumping checkpoint time and dumping checkpoint time. Although **Track-memory** method is longer, but it provides the less frozen time to the container that improves CPU's utilization.

Third, Restoring the container to the container which has already been created in the Swarm Node. Except NFS with memory, they all have nearly performance.

Final, it has big disparity of the delete checkpoint image step at **Track-memory** method, because it has more image files and directories than the version without pre-dumping version.

After all, the checkpoint and restoration of container in memory is faster than hard disk in NFS. As result of Figure **??**, NFS with memory has the best performance in this experiment.



	Native	NFS-tmpfs	NFS-tmpfs-track-memory	NFS	NFS-track-memory
Create container		319.20	310.00	300.80	295.55
Pre-dump	133.88		225.08		657.86
Checkpoint-track-memory	754.36		631.95		2080.38
Checkpoint	990.69	858.41		2385.28	
Restore-track-memory	1346.70	992.76		1294.80	
Restore	1294.80		891.65		1358.67
Remove container		1020.29	1099.38	1198.54	959.44
Delete checkpoint		5.44	59.43	5.43	467.28

Create container Pre-dump Checkpoint-track-memory
Checkpoint Restore-track-memory Restore
Remove container Delete checkpoint

Figure 4.1: Docker Swarm migration with remote storage server

4.3 The Influence of Container Checkpoint Time on Container Process Time

In this experiment, sysbench[14] is used to test performance of process's CPU execution time. Our parameter of sysbench is:

sysbench –test=cpu –cpu-max-prime=20000 run

It will run around 30 seconds in native container without dumping any checkpoint.

In Figure 4.2, this figure lists every checkpoint time in the experiment environments, also, if remote server uses the memory to save the checkpoint images, it will

got better performance. In the checkpoint restore rescheduling policy (section 3.4), we set a parameter of checkpoint-ticker period T_i which will checkpoint repeatedly for every checkpoint-ticker over. As Figure 4.3, the result of the checkpoint-ticker period T_i is in direct ratio to the container process execution time. As observe the result, if the remote storage server doesn't use memory, and the checkpoint-ticker period T_i is smaller than 5, container will take over a half native execution time at dumping checkpoint image. If the checkpoint-ticker period T_i is smaller than 3, container even will take over twice times larger than the native container process execution time.

As these experiment results, the checkpoint-ticker period T_i has a big influence of container execution time, it is an important parameter in checkpoint restore rescheduling policy that if T_i is too small, the container will get a bad performance. But if T_i is too big, whenever Swarm Node fails, the restore container needs to execute the process again. The worst, it might lose some important data. However, no matter the total checkpoint time in **Track-memory** method, the process's execution time are nearly **Direct** method. This situation shows that the pre-dump checkpoint time has no influence on the process's execution time.

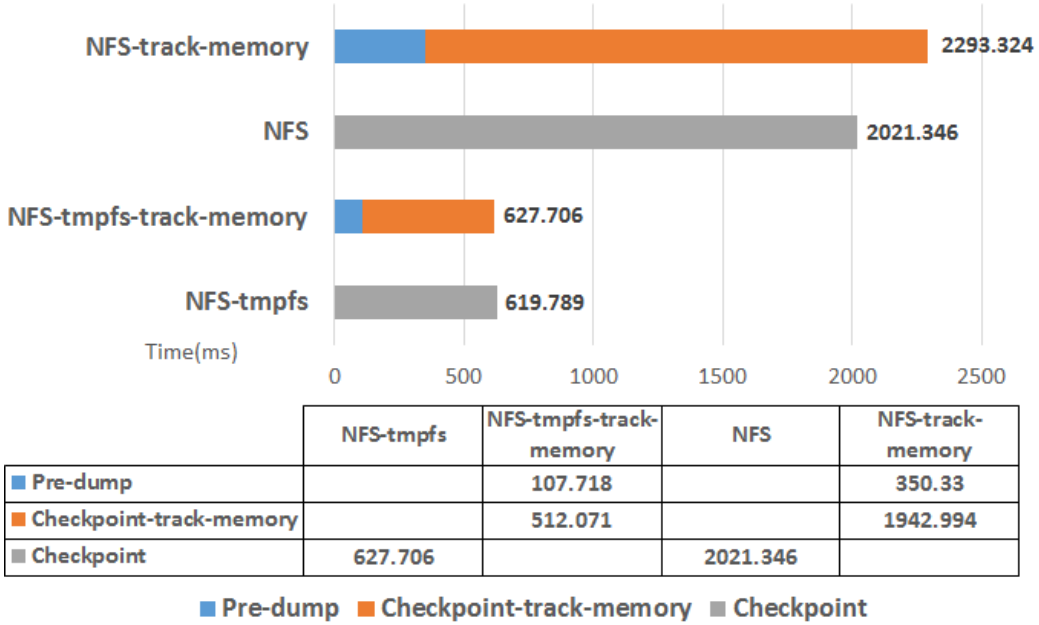
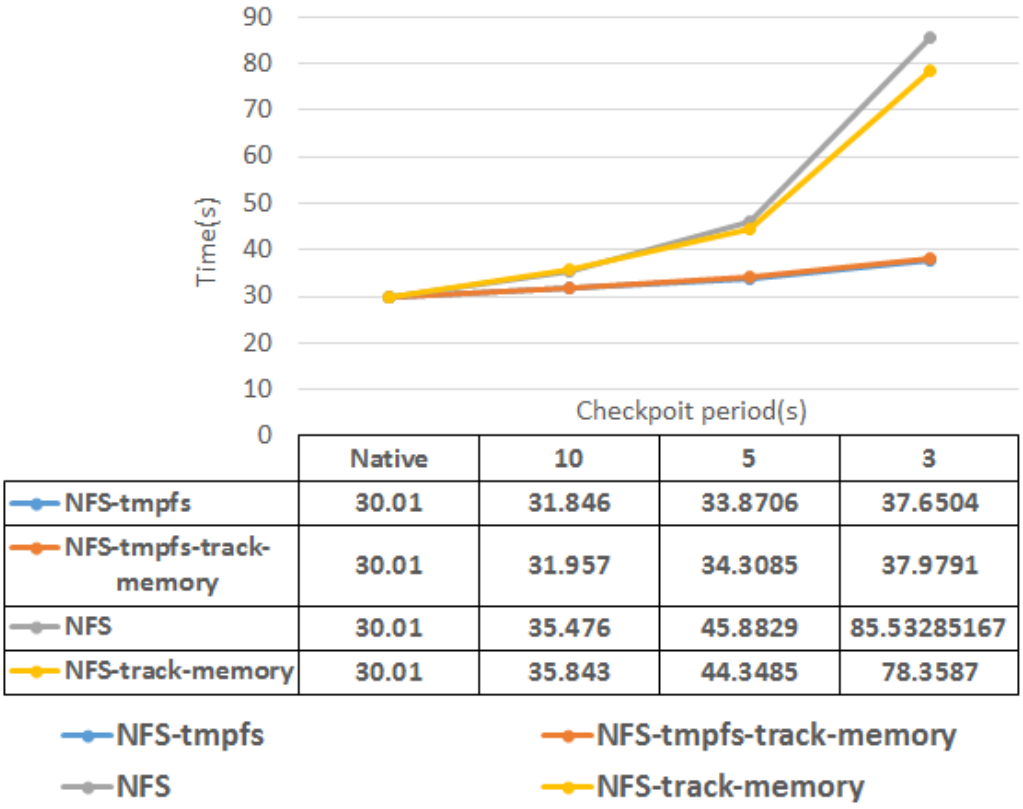


Figure 4.2: Container checkpoint time of container process time



	Native	10	5	3
NFS-tmpfs	30.01	31.846	33.8706	37.6504
NFS-tmpfs-track-memory	30.01	31.957	34.3085	37.9791
NFS	30.01	35.476	45.8829	85.53285167
NFS-track-memory	30.01	35.843	44.3485	78.3587

Figure 4.3: ontainer Checkpoint Time Influence of Container Process Time

4.4 The Influence of Container Memory Size on Container Checkpoint Time

In this experiment, there are 3 different memory size processes measured. These processes allocate 1 MB, 100 MB, and 1 GB and change the memory with random values quickly in a while loop.

As shown in Figure 4.4, the pre-dump checkpoint time is at most 1/5 of the checkpoint time and track-memory checkpoint time is about the same as checkpoint time.

However, in Figure 4.5, the pre-dump checkpoint time is almost a halt of the checkpoint time in the 100 MB process. In this scenario, the track-memory checkpoint time is still nearly as checkpoint time, but the total checkpoint time is about 1.5 times longer then checkpoint time without track-memory, it means when every version-group is created, the first total checkpoint time is 1.5 times longer then **Direct** method's checkpoint time .

In the 1 GB process, Figure 4.6 shows that the pre-dump checkpoint time is almost as same as the checkpoint time. It situation shows that the total checkpoint time is about 2 times longer then **Direct** method when every version-group is created.

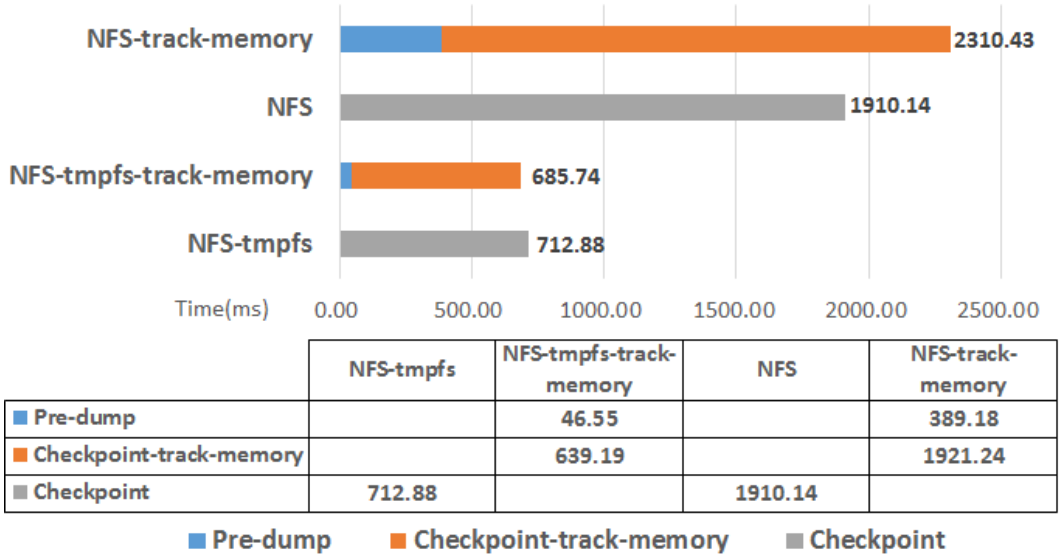
In contrast, If the process has allocated the memory but didn't use it, the result will show as Figure 4.7. This figure shows whatever how many memories are allocated in the process, the pre-dump checkpoint time and checkpoint time are all smaller than the process which is allocated memories with changing it.

Follow these experiments, the memory's change has a big influence about container checkpoint time. It is not a effectiveness way when the process need to change memory a lot in the checkpoint-ticker period T_i time.

4.5 The Influence of Container Memory Usage on Container Checkpoint Image Size

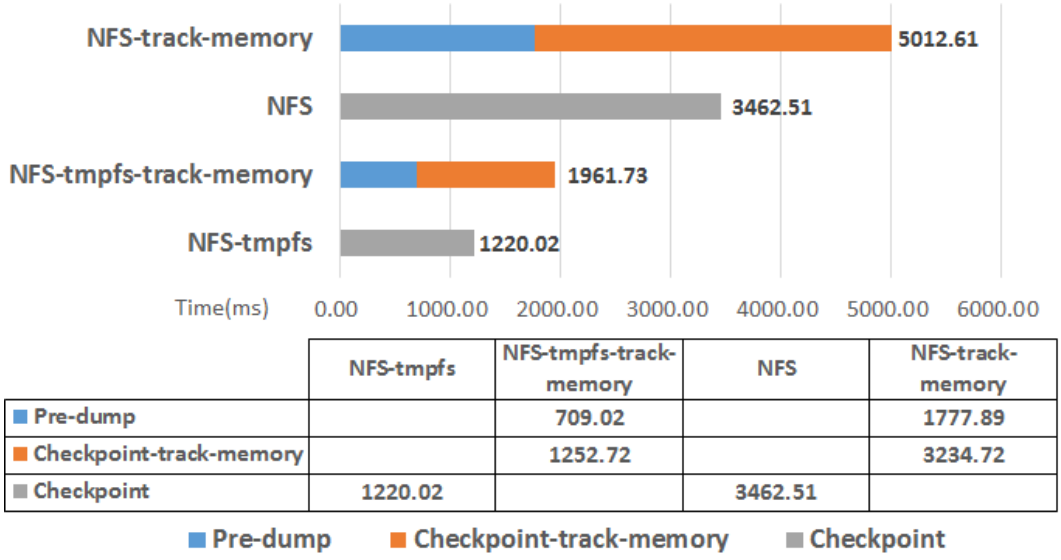
In the section 4.4, the container checkpoint time is direct ratio to process memory usage. In this section, the checkpoint images size will be estimated.

In Table 4.3, it shows that the experiments in the section 4.4. If the process uses



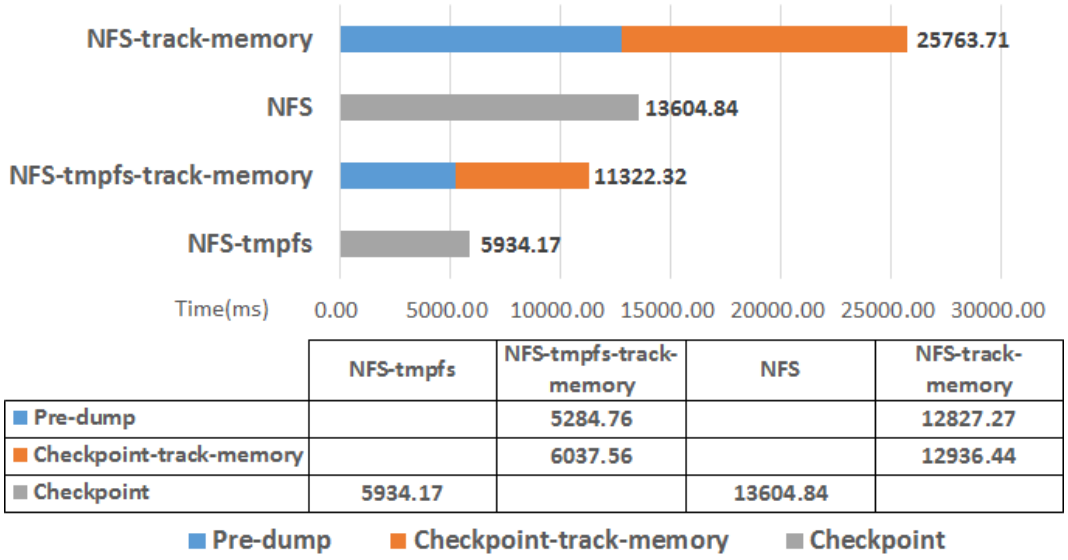
	NFS-tmpfs	NFS-tmpfs-track-memory	NFS	NFS-track-memory
Pre-dump		46.55		389.18
Checkpoint-track-memory		639.19		1921.24
Checkpoint	712.88		1910.14	

Figure 4.4: 1MB container process's checkpoint time



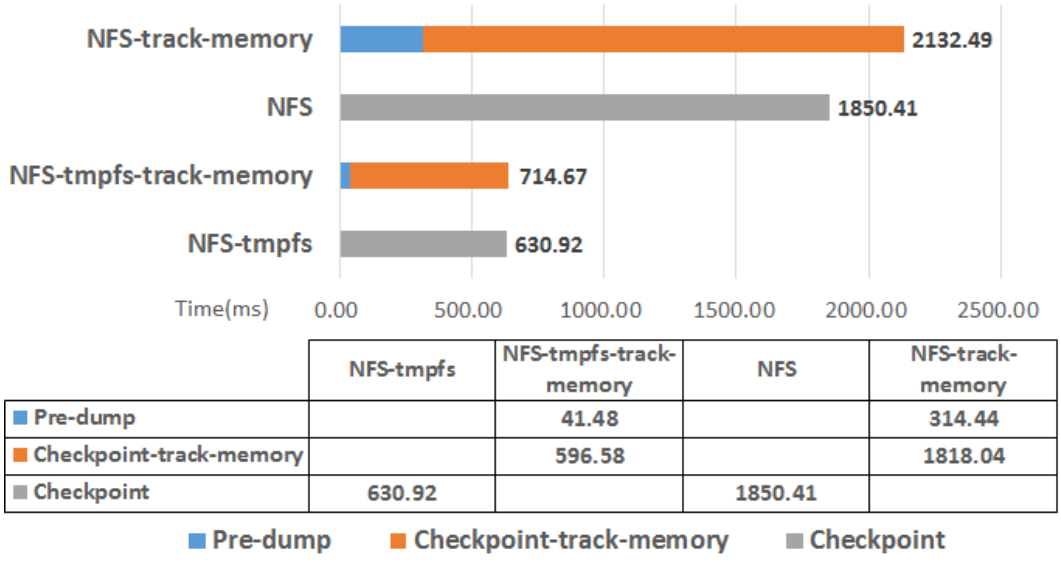
	NFS-tmpfs	NFS-tmpfs-track-memory	NFS	NFS-track-memory
Pre-dump		709.02		1777.89
Checkpoint-track-memory		1252.72		3234.72
Checkpoint	1220.02		3462.51	

Figure 4.5: 100MB container process's checkpoint time



	NFS-tmpfs	NFS-tmpfs-track-memory	NFS	NFS-track-memory
Pre-dump		5284.76		12827.27
Checkpoint-track-memory		6037.56		12936.44
Checkpoint	5934.17		13604.84	

Figure 4.6: 1GB container process's checkpoint time



	NFS-tmpfs	NFS-tmpfs-track-memory	NFS	NFS-track-memory
Pre-dump		41.48		314.44
Checkpoint-track-memory		596.58		1818.04
Checkpoint	630.92		1850.41	

Figure 4.7: Allocated memory without change process's checkpoint time

more memory, the checkpoint image size will be larger. However, although process allocates memory a lot, the checkpoint size still small unless the memory be used.

In Table 4.3, it shows that track-memory version of checkpoint is useless, because it takes more checkpoint time and more storage spaces. To change this view, we test Redis benchmark for daily application. The redis-benchmark command is:

redis-benchmark -t set -l

This command will send 100000 requests with 50 parallel clients. The results shown as table 4.4, the pre-dump checkpoint image size is similar as checkpoint image size, but the track-memory checkpoint image size is smaller than the others. This experiment result shows that the Table 4.3 is the worst case in checkpoint image size. In this case, if track-memory checkpoint is used, it will save more than 2 times storage space.

	1 MB	100 MB	1 GB	Allocate memory without changing
Pre-dump	1 MB	100 MB	1 GB	102 KB
Checkpoint-track-memory	1 MB	100 MB	1 GB	90.9 KB
Checkpoint	1 MB	100 MB	1 GB	175.2 KB

Table 4.3: Process allocated memory's checkpoint image size

	Redis	Redis-benchmark
Pre-dump	9 MB	14 MB
Checkpoint-track-memory	2.3 MB	2.3 MB
Checkpoint	9.6 MB	14 MB

Table 4.4: Redis and Redis benchmark's checkpoint image size

Chapter 5

Conclusion

CRIU provides the container for dumping the checkpoint image and restoring it in the single host machine. In this thesis, we have purposed it to expand to Docker Swarm in the cluster. To support high availability in the Docker Swarm cluster, we also use checkpoint ticker and restoration to recover last container work state in the other Swarm Node. In addition, We implement pre-dump checkpoint to reduce container frozen time and storage spaces; in many cases, it saves about 10% 20% frozen time and at least 200% storage usage.

In the future, we plan to live migration the Docker container to support network applications' migration. In addition, we want to extend power consumption algorithm in Docker Swarm to enhance power consumption saving in the Docker Swarm cluster.

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