Towards a More Reliable and Available Docker-based Container Cloud

Mudit Verma
IBM Research

Mohan Dhawan
IBM Research

Abstract

Operating System-level virtualization technology, or containers as they are commonly known, represents the next generation of light-weight virtualization, and is primarily represented by Docker. However, Docker’s current design does not complement the SLAs from Docker-based container cloud offerings promising both reliability and high availability. The tight coupling between the containers and the Docker daemon proves fatal for the containers’ uptime during daemon’s unavailability due to either failure or upgrade. We present the design and implementation of HYDRA, which fundamentally isolates the containers from the running daemon. Our evaluation shows that HYDRA imposes only moderate overheads even under load, while achieving much higher container availability.

1 Introduction

Container or OS-based virtualization is becoming increasingly popular to provide isolation for applications by leveraging the same underlying OS kernel [18–20]. While several commercial container implementations [4, 10] exist, Docker [4] provides an easy to use application packaging and distribution mechanism, resulting in increased popularity, and several Docker-based container cloud offerings from Google [8], IBM [5], Microsoft [17], Joyent [6], amongst others.

While these Docker-based cloud services offer strict SLAs promising both reliability and availability, just like VM-based clouds, the existing Docker architecture itself becomes a hindrance. Specifically, the spawned containers are direct descendants of the Docker daemon (see Fig. 1), which is responsible for container creation, state management, and monitoring and communication with the containers. This tight coupling between the daemon and the containers makes the daemon a single point of failure, thereby causing the daemon’s unavailability to affect the containers’ uptime. Although, containers (along with their applications) do not require the daemon’s presence for their functioning, Docker still aborts all containers upon a daemon restart, crash or upgrade.

Reliability of the Docker daemon has been discussed recently [1–3] in the context of container clouds. Kubernetes reported several Docker daemon crashes due to Docker bugs, out-of-memory/disk errors, corrupt Docker pulls, etc., immediately aborting all containers. In IBM’s container cloud, all running containers must be aborted upon every Docker upgrade, which occurs frequently.

The above problem is an example of how a single point of failure impacts the entire system. While it has been solved in other contexts, the problem is relevant for today’s Docker-based container cloud, where different containers running on a server might belong to same or different clients and might host highly available or stateless services. In such scenarios, a container downtime caused by external factors such as a daemon’s death/upgrade, is highly undesirable.

We present the design (§2) and implementation (§3) of HYDRA, which decouples the Docker daemon and the containers without affecting any functionality. Specifically, HYDRA re-organizes the process dependencies amongst the daemon and containers such that the running containers and daemon are siblings in process tree, and are not affected even in case of daemon’s unavailability.

We have built a prototype of HYDRA, and our evaluation (§4) shows that HYDRA allows upgrades to the daemon without aborting any containers. Furthermore, with 500 Redis and 200 Tomcat containers, HYDRA improves launch latencies by ~53% (or 800 ms) and ~33% (or 190 ms), respectively, over vanilla Docker. Additionally, while Docker daemon’s resident memory utilization increases linearly with the number of containers, HYDRA daemon’s memory usage increases by just 10 MB up to 20 MB even for 500 Redis containers, i.e., a saving of ~92% over vanilla Docker.

2 HYDRA

We identify broad design goals for a highly reliable and available container architecture as follows:
(1) **Minimal container downtime**: Daemon unavailability must not affect a container’s uptime, and container applications must continue functioning as normal.

(2) **High daemon availability**: The daemon must have minimal downtime. In the event of a crash, it must recover its previous state quickly.

(3) **Low overhead**: Improvements in reliability and availability must not adversely impact the control plane operations between the daemon and the containers.

Lastly, while it would be desirable to seamlessly retrofit existing Docker deployments with the above properties, we do not make it a focus of this work.

2.1 **Design**

**Key Idea.** HYDRA re-architects the process dependencies to eliminate strong coupling between containers and the daemon. Specifically, HYDRA leverages the observation that an orphaned Linux process is adopted naturally by the top-level INIT process. Thus, HYDRA decouples a container process from the daemon just after the container’s first process is spawned, such that the container and the daemon become siblings in the process hierarchy.

In HYDRA, on receiving a client request to create a container, the daemon first spawns a per-container monitor process, which subsequently spawns the container. Once the container process starts, the monitor replaces itself (using UNIX exec) with an ultra-lightweight code, whose primary responsibility is to assist in communication between the container and the daemon. HYDRA then daemonises the monitor, i.e., the parent-child relationship between the daemon and the monitor is decoupled, following which the orphaned monitor (along with its container) is adopted by the top-level INIT. Fig. 2 shows the process hierarchy for HYDRA.

### 2.1.1 Per-container monitor process

HYDRA’s per-container monitor is stateless. However, it is responsible for communicating container’s state to the daemon, and managing its interaction with the Docker client. The monitor must communicate the container’s (a) pid (when the container is spawned), and (b) exit status (when the container finishes execution), for state management within the daemon. In order to reproduce all Docker functionality, the monitor must enable mechanisms to attach and re-direct I/O streams to the client.

2.1.2 **Daemon – container communication**

Docker currently leverages the parent-child hierarchy for communication between the daemon and containers. For example, the daemon performs a `wait` on the container process in a separate thread to determine its execution status. However, with the restructuring of this process hierarchy in HYDRA, these control plane communication channels between the daemon and the containers no longer exist. In order to retain the existing Docker functionality, HYDRA facilitates all control plane operations leveraging out-of-band communication mechanisms between the daemon and the per-container monitor process.

(1) **Container to daemon**: The container to daemon communication is mediated by the monitor process. Once the container terminates, the waiting monitor process in HYDRA (i) writes the exit status in a file, (ii) sends a special signal (like `SIGRTMIN`–`SIGRTMAX`, `SIGUSR1`, `SIGUSR2`) to the daemon to read the file, and (iii) exits itself. If the daemon is unavailable or dead, then upon a subsequent restart, the daemon reads the saved state from the file and performs the necessary state management.

(2) **Daemon to container**: The daemon communicates with the container through direct signaling. The per-container monitor process informs the daemon of the container’s `pid` at its launch, following which the daemon can send management instructions to the container (i.e., stop, pause, kill, continue) using signals like `SIGTERM`, `SIGSTP`, `SIGKILL`, `SIGCONT`, etc.

(3) **Control plane I/O**: HYDRA leverages interprocess pipes to redirect all I/O streams (`stdin`, `stdout` and `stderr`) between the Docker client and the containers.

2.2 **Availability and Reliability**

In event of a daemon restart, following a crash or upgrade, Docker reboots all previously executing containers associated with the daemon. HYDRA, however, does
not terminate any running container, since the contain-
ers are not tied to a particular daemon instance. Thus, HYDRA, by design, avoids container downtime due to daemon unavailability.

Decoupling the parent-child association of the daemon and the containers allows per-container monitor processes to communicate with any instance of the daemon, since, unlike existing Docker implementations, no particular daemon owns the container in HYDRA. Thus, in principle, this distributed association will help HYDRA achieve high availability for the daemon itself, by scaling up the daemon instances on the same/different host(s) and performing load balancing on the distributed requests from the CLI or remote APIs.

**Recovering from a Monitor Crash.** HYDRA does not eliminate the possibility of container downtime. While the monitor process may itself be terminated inadvertently, it would affect just a single container. In the event of a monitor crash, the orphaned container is adopted by the INIT, and continues to function normally without any downtime. However, the daemon has no way to control/interact with such a container. HYDRA’s daemon overcomes this problem by (a) maintaining a list of pid for both the monitor and the container, and (b) periodic polling for the monitor processes in a dedicated thread. When the daemon detects a live but orphaned container (based on the pid associations), it forcefully takes down and reboots the container, thereby maintaining connectivity with the monitor and the container.

### 2.3 Lazy-HYDRA ($\ell$-HYDRA)

In lazy HYDRA, the newly spawned monitors (along with their containers) are initially direct children of the daemon, as in current Docker implementation. However, upon daemon failure (due to crash or upgrade), all the monitors (along with their running containers) become orphan and are adopted naturally by the top-level INIT process. Fig. 3 presents the process tree for $\ell$-HYDRA. While equivalent to HYDRA in functionality, $\ell$-HYDRA’s design has less homogeneity, with currently spawned monitors (along with containers 1 and 2) attached as descendants of the current daemon instance, and orphaned monitors along with containers 3 and 4 (due to a previous daemon crash) attached to the INIT process.

### 3 Implementation

We enhance vanilla Docker v1.8.0 to build a prototype of HYDRA (per §2.1). We below describe key features of our implementation.

- **Monitor creation:** On every new container spawn, HYDRA daemon double forks the Docker binary. The last forked Docker process further spawns the container process as its descendant and subsequently replaces itself (using UNIX exec) with a lightweight monitor code.
- **Process hierarchy re-organization:** Once the monitor creation is complete, the monitor kills its parent, i.e., a forking intermediate process, using ppid and UNIX kill, thereby daemonising itself. The monitor (along with its container) is then adopted by INIT, thereby completing the re-organization of the process hierarchy.
- **Out-of-band communication:** The monitor implements a wait on its descendant container process in a thread, and supplies the container’s exit status to the daemon by (a) writing to a specific file (named by the containerId) at a pre-defined path in the container’s workspace, and (b) sending a special signal SIGRTMIN+10 from the reserved signal pool SIGRTMIN-SIGTMAX to the daemon, which upon receiving this signal, reads the exit status from the designated file. In another thread, the monitor implements an API server, which listens to its own unique socket (containerId.sock). The daemon maintains and supplies this socket information to the Docker client, following which the client connects directly to the monitor for container I/O redirection.

**HYDRA** required modifications to $\sim$1300 LOC across 25 files, impacting just 12 of the total 40 Docker commands. The above changes represent $<1\%$ of Docker’s code base in terms of LOC, and $<3\%$ in terms of the total files. Thus, only minimal changes are required to significantly enhance the reliability and availability of the containers. We also implemented $\ell$-HYDRA as described in §2.1. $\ell$-HYDRA leverages most of HYDRA’s code base except that it requires single fork (instead of a double fork described above), and also does not need subsequent daemonising of the monitor.

### 4 Evaluation

In §4.1 we demonstrate the reliability provided by HYDRA under varying conditions, and quantify the impact of a daemon crash on daemon, container and application. In §4.2 we measure perceived end user latencies for HYDRA. Lastly, in §4.3 we compare scalability of HYDRA against vanilla Docker.

**Experimental Setup.** All experiments were performed on a virtual machine provisioned with 16 cores at 2.0 GHz, 32 GB RAM, and running 64 bit Ubuntu v14.04. We compare HYDRA and $\ell$-HYDRA against vanilla Docker v1.8.0. Unless stated, we evaluate $\ell$-HYDRA considering a daemon that has not abruptly crashed, i.e., new containers attach to the daemon’s process hierarchy. Further, all experiments (except §4.3) assume no previously running containers, and use official, unmodified container images.

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1The affected Docker commands are attach, exec, kill, pause, restart, run, start, stats, stop, top, unpause, and wait.
4.1 Reliability

A daemon restart entails (i) restoring daemon state, (ii) rebooting all previously running containers, and subsequently (iii) initializing container applications to make them operational. In the experiments below, we first launch an application container and subsequently kill the daemon process. We then compute savings for both HYDRA and \(\ell\)-HYDRA over vanilla Docker on a daemon restart by measuring time to restore the daemon and containers, and time to complete application initialization (after container has been restored). We also measure the perceived application outage due to Docker upgrade.

(i) **Daemon restart.** Redis is a light-weight application that runs few processes and has low initialization time, while Tomcat is a heavy-weight application with several processes and high initialization time. Thus, both Redis and Tomcat lie at opposite ends of the application spectrum. We repeat each experiment 1K times with just one running container. Further, default log levels, and container and application configurations were enabled.

- **Daemon:** Fig. 4a shows a CDF of the state restoration time for the daemon upon a restart from a crash. We note that across both the applications, the daemon state restoration time remained fairly consistent at < 40 ms for HYDRA, \(\ell\)-HYDRA and vanilla Docker.

- **Container:** Unlike Docker, HYDRA and \(\ell\)-HYDRA do not need to restore previously running containers, since their containers do not abort on a daemon crash. Instead, HYDRA and \(\ell\)-HYDRA simply read state from already running containers, leading to lower container restoration time. Fig. 4b shows the results. We note that across the benchmarks, HYDRA and \(\ell\)-HYDRA report container restoration times \(~100\) ms lower than vanilla Docker.

- **Application:** Since a daemon crash does not impact running containers in HYDRA and \(\ell\)-HYDRA, the application startup time is applicable only for vanilla Docker setup. Note that initialization depends significantly on the nature of the application. Our experiments reveal that after a restart, Redis completed initialization in \(~2\) ms, while Tomcat required \(~1039\) ms. Furthermore, restart times may be lower than that of fresh application starts, especially for stateful applications, like MySQL, which reloads stored persistent state upon restart. For example, we observed that a fresh initialization for MySQL required \(~5600\) ms, while a restart took just \(~300\) ms.

(ii) **Outage during upgrades.** We select 10 popular, but diverse, official container images (with each having several million downloads), and measure the user perceived application outage due to an upgrade from v1.8.0 to v1.8.3 for vanilla Docker. Recall that both HYDRA and \(\ell\)-HYDRA do not incur any container downtime. We perform each experiment 10 times, and report the average application outage in Fig. 4c. We observe that both HYDRA and \(\ell\)-HYDRA save upon application outages of several seconds as compared to Docker.

### Table 1: User perceived latencies for starting a container.

| Image      | App. Init. | Docker | HYDRA | \(\ell\)-HYDRA |
|------------|------------|--------|-------|----------------|
|            | Time (ms)  | Time (ms) | Time (ms) | (%) | Time (ms) | (%) |
| Cadvisor   | 2256       | 2503   | 2037  | 5.6          | 2625  | 4.9 |
| Elasticsearch | 5187      | 5452   | 5548  | 1.8          | 5527  | 1.4 |
| Mariadb     | 9010       | 9258   | 9379  | 1.3          | 9348  | 0.9 |
| Mongodb     | 983        | 1217   | 1355  | 11.3         | 1318  | 8.3 |
| Mysql       | 5621       | 5848   | 5975  | 2.2          | 5947  | 1.7 |
| Postgres    | 4840       | 5079   | 5198  | 2.3          | 5171  | 1.8 |
| Rabbitmq    | 3002       | 3291   | 3373  | 2.5          | 3360  | 2.1 |
| Redis       | 2          | 228    | 340   | 49.1         | 316   | 38.6 |
| Tomcat      | 1039       | 1324   | 1453  | 9.4          | 1417  | 6.7 |
| Zookeeper   | 3153       | 3406   | 3495  | 2.6          | 3463  | 1.7 |

An important measure of performance is the perceived end user latency for spawning a container. We use the 10 previously selected benchmarks (as listed in Fig. 4c), and measure the time to completely spawn a container, which includes both the daemon and monitor instantiation, along with the application startup time. Note that, unlike §4.1 application startup here corresponds to a fresh start with no application specified persistent state, and could thus be significantly more than just restart times, especially for stateful applications, like MySQL.

We perform the experiment 10 times and measure the absolute time and relative overheads for every container spawn, for HYDRA, \(\ell\)-HYDRA, and vanilla Docker. Table 1 reports the average time and overhead for each benchmark. We note that most benchmarks, except Mon-
godb, Redis and Tomcat, incur low relative overheads ($\leq 5\%$) since the application startup time masks the overhead due to monitor creation and re-organization of the process hierarchy (as described earlier in §3).

We further breakdown the absolute times for HYDRA, and observe that the latencies due to monitor creation and re-organization of the process hierarchy varies between 80-140 ms. Due to the single process fork for monitor creation in $\ell$-HYDRA, unlike the double fork in HYDRA, this latency drops slightly and ranges between 60-120 ms. Thus, benchmarks with application startup times comparable with these latencies, such as Mongodb, Redis and Tomcat, incur high relative overheads.

### 4.3 Scalability

We determine HYDRA’s impact on scalability by measuring the time taken to launch an $(n+1)^{th}$ Redis or Tomcat container, with $n$ stable containers already executing. Fig. 5a and 5b show a log-scale variation in latencies to launch subsequent Redis and Tomcat containers, for both HYDRA and vanilla Docker. Note that we could not spawn more that 200 Tomcat containers on our VM, due to their high memory requirements. Redis posed no such issues, and we easily spawned 500 containers.

We observe that for vanilla Docker the launch latencies increase linearly as the number of containers increase. In contrast, even though HYDRA incurs higher container launch overheads initially, it significantly reduces these overheads as we scale. Specifically, with 500th Redis and 200th Tomcat container spawn, HYDRA improves launch latencies by ~53% (or 800 ms) and ~33% (or 190 ms), respectively, over vanilla Docker. When operating at scale, these savings in HYDRA primarily stem from not having (a) wait threads for each container within the daemon, and (b) a bloated daemon process hierarchy (as in vanilla Docker) that significantly increases subsequent container fork latencies [15].

Additionally, while Docker daemon’s resident memory utilization increases linearly with the number of containers, HYDRA daemon’s memory usage increases by just 10 MB up to 20 MB even for 500 Redis containers, i.e., a saving of ~92% over vanilla Docker. This minor increase in memory usage is due to the container state accumulation in the HYDRA daemon. In contrast, Docker daemon manages several GO [13] runtime threads, including a wait thread, for every container launched. Each of these additional threads accumulate memory and contribute to the high resident memory usage of the Docker daemon. Fig. 5c plots these results.

### 4.4 Threats to validity

While the benchmarks used for evaluation are representative of the popular container applications used in practice, our evaluations were performed under a controlled setting within a virtual machine. It is possible that a combination of compute and/or memory intensive load might induce performance behaviors not captured in our study.

### 5 Related Work

Like HYDRA, both rkt [13] and runC [12], ensure container reliability, and in the worst case, just one container is impacted. However, unlike HYDRA’s light-weight monitor, both these tools attach a separate heavy-weight execution engine to each container, thereby increasing the system’s memory footprint. Furthermore, HYDRA is compatible with the entire Docker eco-system, while rkt is still not widely adopted, and runC is under active development and lacks many useful functionalities.

LXD [10] is a container “hypervisor” to manage containers. It implements a REST API atop LXC [9], a system container runtime, and forks a monitor and container process, which ensures that the LXD daemon is not a central point of failure and containers continue running in case of LXD daemon failure. Even though architecturally similar to HYDRA, LXD is closer in functionality to KVM [7], a full system virtualization platform.

OpenVZ [11] is a system container runtime designed to execute full system images. In contrast, systemd-nspawn [14] handles only process isolation and does not enable resource isolation. HYDRA on the
other hand enhances reliability and availability of containers that leverage the Docker runtime.

6 Conclusion

We present HYDRA, a system that re-architects the process hierarchy in Docker to significantly enhance reliability and availability of the containers, while imposing only moderate overheads. Container cloud offerings built atop HYDRA would enable a more reliable and available execution environment.
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