COLONIES - COMPUTE CONTINUUMS ACROSS PLATFORMS

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ABSTRACT

Artificial intelligence and machine learning has gained significant traction in recent years. At the same time, development and operation of AI workloads has become increasingly challenging. One difficulty is the lack of portability, making it cumbersome to move from one platform to another. Creating and operating fully automated end-to-end workflows across devices, edge, and cloud platforms is even more challenging.

To address the aforementioned challenges, the paper introduces a framework termed Colonies designed to facilitate the execution of computational workloads across a diverse range of platforms. Colonies is founded upon a loosely-coupled microservice architecture that beaks down complex workflows into composable functions. With the use of an HTTP protocol, these composable functions can be implemented in any computer language and be executed by independent executors deployed across various systems, e.g. cloud, edge, devices, or even in web browsers. Colonies orchestrates the execution and by using a zereo-trust security protocol, a collection of distributed executors can function as a single cohesive unit, thereby establishing a seamless compute continuum across multiple platforms.

In addition to a technical description of the Colonies framework, the paper also describes some potential use cases. The paper describe how Colonies can be leveraged to build a remote sensing platform on Kubernetes, serve as a building block for edge computing, implement a serverless FaaS (Function-as-a-Service), and how it can be integrated with HPC platforms. Finally, the paper presents a performance investigation, as well as scalability and robustness evaluation.

In summary, Colonies is a highly versatile and scalable framework that can streamline the development and deployment of computational workloads across heterogeneous platforms while also ensuring full traceability and zero-trust security.

Keywords Serverless computing · Parallel computing · Workflow orchestration

1 Introduction

Developing robust and scalable AI systems is a challenging task that requires deep understanding in several fields. To begin with, an AI model must be trained which requires knowledge in advanced statistics or machine learning, as well as access to training and validation data. Typically, this data must be pre-processed through various stages before it can be utilized. Although it may be practical for small-scale projects to run the entire training processes on local development computers, larger AI models typically require access to powerful compute clusters or even HPC systems. Manual use of such infrastructure can be laborious and time-consuming. Automating the training process enables faster iterations and quicker discovery of useful models.

Taking an AI model into production requires substantial software engineering expertise. In contrast to traditional IT workloads, both the data and the model must be managed in addition to the software itself. As most models require regular re-training or re-calibration, it must be possible to update deployed models and software seamlessly without losing information or breaking the system. In many cases, there is a constant flow of data ingested into the system which must be managed even if some components are malfunctioning. This becomes even more challenging when nodes or parts of the underlying infrastructure become unavailable due to maintenance or failaure such as software updates, hardware replacements or simply missconfiguration.

In some cases, it may be necessary to scale the system to increase or reduce the capacity. This is especially critical when using expensive cloud resources. Scaling the system means that the underlying infrastructure may change at any time, causing instability issues for running services or workflows. Therefore, it must be possible to detect failed computations and reprocess failed tasks part of a larger workflow. Workflows must hence be designed to handle an ever-changing infrastructure, and if a failed computation cannot be restored gracefully, engineers must be able to quickly perform root cause analysis to manually recover the system.

In reality, AI system requires integration of multiple systems. For instance, data may need to be captured from an IoT system or pulled from third-party database running on different domains than the compute cluster. With the emergence of edge computing, parts of a data pipeline may also run on edge servers to bring computations closer to data sources. Configuring and setting up such pipelines add even more complexity.

Additionally, many compute clusters operate on-premises installations. Sometimes it is necessary to temporarily increase the capacity of on-prem clusters by combining resources from multiple providers, for example, adding cloud compute resources to handle peak loads or utilize HPC resources to quickly reprocess historical data. Developing hybrid workflows where some jobs run in the cloud and others run on HPC systems requires even more software development efforts and is beyond the scope of most users, preventing them from utilizing powerful hardware. Clearly, there is a need for a framework that can consolidate various platforms to simplify development and enable seamless execution across platforms.

This paper presents a framework called Colonies, which is built around a loosely-coupled microservices architecture that separates workflow definitions from implementation and deployment. The main objective is to create a tool where monolithic workflows can be broken down into independent and separated compute units that can be dynamically added or removed while executing workflows. These compute units can be implemented in any computer language and be deployed anywhere on the Internet.

2 Related work

A workflow is a series of tasks that need to be completed in a specific order. Workflows are often represented as directed acyclic graphs (DAGs), where nodes represent tasks and edges represent dependencies or data flow between tasks. Workflow management has been extensively studied in both academic and industrial settings, with numerous approaches proposed to address the challenges in this field.

Another popular approach is the use of workflow engines, which provide a framework for creating and executing workflows. Workflow engines can be integrated with other tools and systems to automate complex business processes. Examples of workflow engines include Apache Airflow, Camunda, and Zeebe.

Apache Airflow is a popular open-source workflow management system used to programmatically author, schedule, and monitor workflows. Luigi is also an open-source workflow management system developed by Spotify. It is designed to handle long-running batch jobs and data pipelines.

Pinball is a workflow management system developed by Pinterest that allows users to define and execute workflows using Python scripts. It has a simple architecture, with support for DAGs and task dependencies. However, it lacks some of the advanced features of Airflow, such as task retries and monitoring.

TODO:

3 The Colonies framework

Microservices is an architectural design pattern in which an application is structured as a collection of small, independently deployable, and loosely coupled services that communicate with other microservices through a well-defined API. By dividing the application into smaller, focused microservices, applications become easier to understand, maintain, and develop. Each microservice can be scaled independently, making it easier to handle increased demand for a certain service. Additionally, different microservices can be developed by using diverse technologies, frameworks, or programming languages, enabling developers to select the most suitable tools for each specific problem. By assigning ownership of specific microservices to individual teams, it also becomes easier to coordinate work and maintain a consistent development process.

Currently, microservices are primarily used to implement large-scale web applications or Internet applications requiring high-availability. It has not yet become a prevalent design principle for workload management or implementation of HPC applications. Instead, simple job scripts are commonly used. In some cases, message brokers (e.g., RabbitMQ) are used to build worker queues to distribute tasks among multiple workers. Although this approach may be effective for simpler applications, creating dependencies between tasks, such as controlling the order of execution or passing information between tasks is not straightforward.

Colonies is based on a microservice architecture where workflows are decomposed into a set of independent functions. An example of a function could for example be a function that trains a neural network, prepare a batch of data, or upload inferred results to a third-party database etc. An executor is responsible for executing one or several functions, making it very simular to a microservice. All coordination is managed by a cluster of Colonies servers, allowing complex workflows to be broken down into independent functions that can be developed and tested separately. Analogous to traditional microservices, scalability can be achieved simply by adding more executors implementing the same function specification. If an executor crashes during task execution, the task is automatically reassigned to another executor.

3.1 The role of queues as seperation of concerns

Separation of concerns (SoC) is a fundamental design principle in computer science that aims to break down a complex software system into smaller, more manageable parts. For example, HTTP APIs can be used to abstract away implementation detail and provide a clear and simple interface for interacting with a particular service. However, HTTP protocols alone are insufficient for handling dynamic environments where components frequently fails or the underlying infrastructures is constantly changing. To address such environments, an alternative mechanism is necessary.

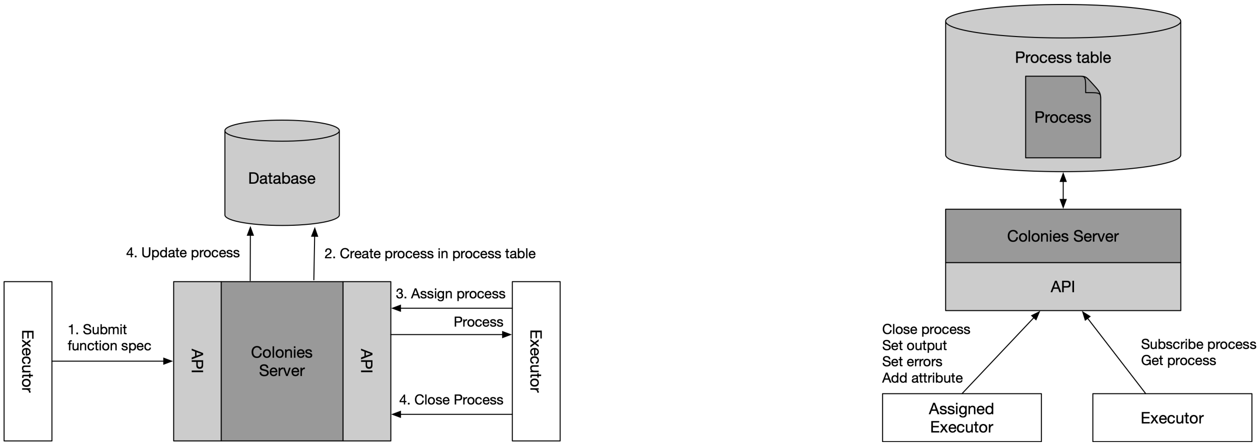
Queues enable different software components to communicate indirectly by acting as a buffer between them. Queues makes it possible to decouple each executor and make them operate independently, e.g. an executor can be updated or replaced without affecting other executors. Queues also allow for asynchronous communication between executors, enabling them to process tasks at their own pace. This ensures that slower executors do not bottleneck faster ones, leading to a more efficient and scalable system. Most importantely, queues enable load balancing by distributing tasks among multiple executors, thus making it possible to parallelize workflow execution.

Queues can be implemented in different ways, and while message brokers are a common solution, Colonies has adopted an alternative strategy by leveraging a standard database and querying it for tasks to assign to different executors. One key advantage of this approach is that it enables fine-grained task assignments, making it possible to assign specific tasks to particular executors. For instance, an executor of the browser type can be limited to only executing tasks of the browser type. This level of granularity cannot easily be implemented using message brokers which generally do not offer introspection of queue, or provide the ability to pull specific messages out of the queue. Generarally, the only way to retrieve a specific message is to pull all messages from the queue, obtain the message, and then place all remaining messages back into the queue in the same order. In contrast, using a database a query can match any columns and be ordered using a timestamp to make it function as a queue.

$$priority_{time} = priority \cdot -10^9 \cdot 60 \cdot 60 \cdot 24 + submission_{time} \tag{1}$$

3.2 Process tables

Colonies provides a platform for executors to interact with each other by enabling them to submit function specifications to a Colonies server. Once submitted, other executors can connect to the server to receive execution assignments. When a function specification is submitted to the Colonies server, it is store as a process entry in a dedicated process table database. In this case, a process is analogous to a task, but contains additional contextual information about the execution, for example, execution status (waiting, running, successful, failed), assigned executor Id, submission time,



(a) Process assignment steps.

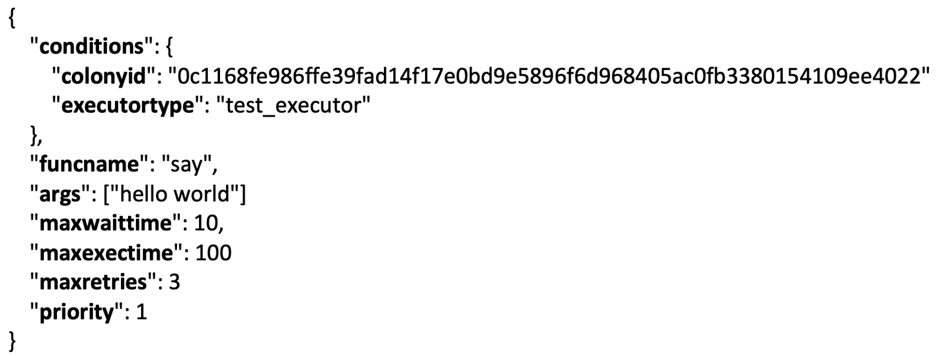
(b) Manipulation of a process.

Figure 1: Process management via Colonies HTTP API. Note that only the assigned executor has write access to the process database entry.

execution time, deadlines, priority etc. It also contains input and argument values as well as return values from the function innovation.

The Colonies server acts as a job broker for executors, almost like an employment agency for people. When an executor connects to the Colonies server, the server hang the incomming HTTP connection[1] until the executor is assigned a process, or until a connection timer expires. Note that the Colonies server does not connect to any executor. Rather, it is the responsibility of the executors to connect to the Colonies server. This enables executors to be deployed anywhere on the Internet, even behind firewalls, commercial telco networks, or in application running in web browsers.

Figure 1 illustrates an executor submitting a function specification that is later assigned to another executor. Executors have to specify to the Colonies server which functions they are capable of executing. The Colonies server makes sure that the conditions (i.e requirmenets) of a function specification matches the capability of an executor.



```
{
  "conditions": {
    "colonyid": "0c1168fe986ffe39fad14f17e0bd9e5896f6d968405ac0fb3380154109ee4022"
    "executortype": "test_executor"
  },
  "funcname": "say",
  "args": ["hello world"]
  "maxwaittime": 10,
  "maxexectime": 100
  "maxretries": 3
  "priority": 1
}
```

Figure 2: Example of a function spec.

Figure 2 shows an example of a function specification. The *maxexectime* attribute specifies the maximum time an executor may run a process (in this case, 100 seconds). Before a process is assigned to an executor, the Colonies server updates the process entry in the process table database and calculates a deadline for when the process must be finished. The server then regularly checks for any running processes that have exceeded their deadlines. If such process is detected, it is reset, allowing it to be re-assigned to other executors. This scheme is completely stateless, so if the Colonies server crashes, another Colonies server can take over and look for processes that have exceeded their deadline. Moreover, if an executor assigned to a process crashes, the process is simply re-executed by another executor.

Making it possible to specify maximum execution time is a simple but powerful mechanism. To scale up a system, more executors can simply be deployed. Scaling down, however, can be more challenging. One solution is to select a set of

[1] An alternative protocol is to use WebSockets or gPRC to communicate with the Colonies server.

executors to be removed and then starv them out by denying them new process assignments. Another, simpler solution, is to immediately destroy the executors, or if possible notify them in advance so that they can gracefully unregister.

The *maxexectime* failsafe mechanism ensures that processes will eventually be executed even in the case of failures. This mechanism also relieves the burden of user to check if a process has been executed or not, as they can simply look up the process in the database to get its current status. The Colonies framework also supports subscribing on process changes using an event-driven protocol, but this may be impractical if a process runs for a very long time (e.g. days or weeks).

Utilizing the *maxexectime* failsafe mechanism not only enhances system reliability, but also provides an opportunity to apply of Chaos engineering [1]. For example, deliberately terminating executors using a Chaos monkey. If executors are deployed on Kubernetes, Kubernetes will automatically redeploy terminated executors. The constant replacement of executor instances ensures that the system is capable of gracefully tolerating failures.

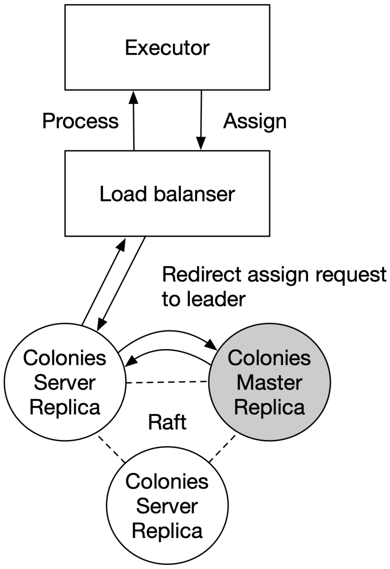


Figure 3: High-availability deployment of Colonies servcer.

3.2.1 Concurreny and synchronization

Synchronization is esstential to prevent data inconsistency and race conditions when accessing shared resources concurrently with multiple threads. However, synchronization can also slows down execution as only one thread can access critical sections at a time. By carefully designing multithreaded applications and employing the right synchronization techniques, it possible to minimize the performance impact while still ensuring data consistency and correctness.

The primary objective of all Colonies API requests is to either alter a state stored in the database or retrieve information from it. The Colonies framework is designed to be stateless, meaning that the Colonies server does not keep any information between requests. In other words, each request is handled independently, without relying on any information from previous requests.

One example of a request is the assign request, which allocates a waiting process from the database to an executor. Given the multi-threaded nature of the Colonies server, it is essential that the assign request is synchronized to ensure that only one thread at a time can modify the database and update the process table, thus preventing multiple executors from being assigned to the same process. As only the assigned executor can modify a running process and only one executor must be assigned to a process, synchronization is required for the assign request. It is worth noting that synchronization is not necessary for other requests, such as the submit request or the close request. As the submit request only add new entries to the process table, there is no race conditions. The close request set the output of the function innovation and updates the process state to either successful or failed in the process table. Since there exists only one assigned executor there is no need for synchronization.

To minimize downtime in the event of hardware or software failures, there is a need for high-availability and make use of a cluster of Colonies servers. If one Coloniser server crashes, an executor simply need to re-send a failed request, which will then be served by another Colonies server replica. However, by introducing multiple Colonies servers, there is again a risk of race conditions when assigning processes to executors. This means that the Colonies server replicas must coordintate which replica server incomming assign requests so that precisely one executor is assigned to a process.

Raft [2] is a consensus algorithm specifically designed to manage a replicated log within a distributed system. It functions within a cluster of servers, where a single server takes on the role of leader while the remaining servers act as followers. The leader is responsible for managing the replicated log, processing client requests, and replicating entries to the followers. Followers passively replicate the leader's log and participate in leader elections. The leadership can change over time due to elections triggered by timeouts or other factors.

Incorporating Raft into the Colonies framework allows incoming assign requests to be directed towards the leading Colonies server, ensuring that only one Colonies server replica handles these requests. Figure 3 shows an overview of a high-availability Colonies deployment. A new leader is elected in the event that a Colonies server replica fails. The Raft protocol also enables seamless updates to the Colonies server software by making it possible to upgrade each replica individually. As a result, Colonies becomes well-suited for Kubernetes deployments.

3.2.2 Workflows

TODO

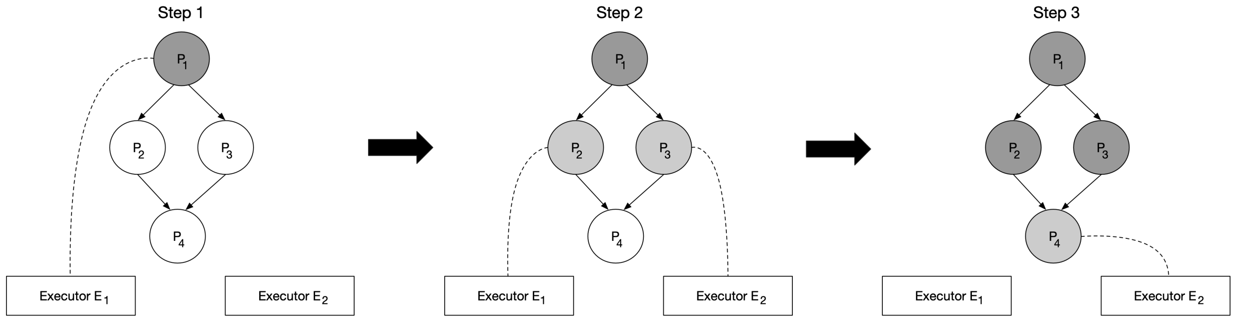


Figure 4: cron management

Table 1: Function Specifications

Function Spec	Function	Executor Type	Priority	Max Exec Time	Max Retries
F_1	gen_nums()	Edge	1	200 s	5
F_2	square()	Cloud	1	200 s	5
F_3	square()	Cloud	1	200 s	5
F_4	sum()	Browser	1	200 s	5

Table 2: Snapshot of Process Table as in Step 2

Process Id	Function Spec	Wait for Parents	Assigned Executor Id	State	Priority Time
P_1	F_1	$False$	E_1	Successful	1679906715352024000
P_2	F_2	$False$	E_1	Running	1679906715353453000
P_3	F_3	$False$	E_2	Running	1679906715354286000
P_4	F_4	$True$	-	Waiting	1679906715355188000

3.2.3 Cron

TODO

3.2.4 Generators

TODO

Table 3: Dependency Table

Process Id	Name	Dependencies
P_1	$Task_1$	-
P_2	$Task_2$	$Task_1$
P_3	$Task_3$	$Task_1$
P_4	$Task_4$	$Task_2, Task_3$

Table 4: Input/Output Table

Process Id	Input	Output
P_1		[2,3]
P_2	2	4
P_3	3	9
P_4	[4,9]	13

3.2.5 Zero-trust security

TODO

4 Evaluation

4.1 Implementation

References

[1] Principles of chaos engineering - the chaos engineering manifesto.

[2] Diego Ongaro and John Ousterhout. In search of an understandable consensus algorithm. In *2014 USENIX Annual Technical Conference (USENIX ATC 14)*, pages 305–319, Philadelphia, PA, June 2014. USENIX Association.

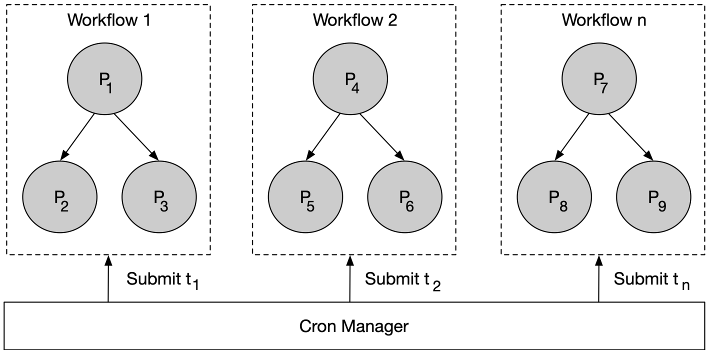


Figure 5: Sample figure caption.