GAVIP: A Platform for Gaia Data Analysis

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ABSTRACT

Gaia is a major European Space Agency (ESA) astrophysics mission designed to map and analyse $10^9$ stars, ultimately generating more than 1 PetaByte of data-products. As Gaia data becomes publicly available and reaches a wider audience, there is an increasing need to facilitate the further use of Gaia products without needing to download large datasets. The Gaia Added Value Interface Platform (GAVIP) is designed to address this challenge by providing an innovative platform within which scientists can submit and deploy code, packaged as “Added Value Interfaces” (AVIs), which will be executed close to the data. Deployed AVIs and associated outputs may also be made available to other GAVIP platform users, thus providing a mechanism for scientific experiment reproducibility. This paper describes the capabilities and features of GAVIP.

Keywords: GAVIP, PaaS, Gaia, collaborative, data processing, platform

1. INTRODUCTION

There is currently more than 1 petabyte (PB\textsuperscript{1}) of astronomy data that is accessible electronically, with archives growing at a rate of 0.5 PB per year. Data rates and sensor sizes are increasing as more new facilities come online, leading to predictions that by 2020 more than 60 PB of archived data will be accessible. The existence of these massive, distributed, and heterogeneous data-sets poses challenges, both to the underlying data curation and infrastructure/archive management and to traditional astronomical research methods. A major challenge for future astronomy missions is that the on-board instruments are so sensitive and have such large fields of view that the volume of data is transcending current working capabilities. Traditionally, astronomers would obtain observations of a source, these data would be downloaded and analysed, and although the analysis can be very complex and may need to be processed on dedicated servers, the data were not prohibitively large as to prevent users downloading products and working locally. This is changing with large scale surveys such as Gaia\textsuperscript{1}, Intermediate Palomar Transient Factory (iPTF)\textsuperscript{2}, Pan-STARRS\textsuperscript{3}, and the Large Synoptic Survey Telescope (LSST)\textsuperscript{4}. These ground and space-based instruments with wide fields of view and/or scanning capabilities now observe the sky continuously, build up all-sky maps regularly and have opened a huge discovery space. Within this context, if the right tools are provided, more and diverse users will be motivated to take advantage of the science within these growing archives.

Gaia is an extremely ambitious and complex ESA mission designed to carry out an all-sky astrometric, photometric and spectroscopic survey of objects brighter than 20 magnitude for astrometric and photometric observations, and 16 magnitude for spectroscopic observations.\textsuperscript{3} It was launched in 2013 and is currently orbiting the second Lagrange point at a distance of 1.5 million kilometres from the Earth in the anti-Sun direction. Gaia will measure of order one $10^9$ objects, including about 1% of the stars in the Milky Way, $10^6$ to $10^7$ galaxies, 500,000 quasars\textsuperscript{5}, and of order 6000 supernova\textsuperscript{6,7,8}. The Gaia scanning law gives the number of times a region will be re-observed over its 5-year mission, and comes from this spinning motion of the satellite and its orbit around the Sun. The average number of observations per object is 70, although it can be as low as a few tens or as high as 200\textsuperscript{9}. During the mission, Gaia is expected to transmit some 150 terabytes (TB) of

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\textsuperscript{1} 1 PB = 1,000 TB
raw data to Earth, leading to production of a catalogue of $10^9$ individual objects. After on-ground processing, the full database is expected to be in the range of one to two PB of data [7].

Consequently, the large volume of data that will ultimately be generated by Gaia means that alternatives to the traditional approach of local data analysis should be investigated. Other more general issues to consider include those related to the reproducibility of scientific experiments, amid a growing concern about irreproducible results†. The Gaia Added Value Interface Platform (GAVIP) is a Python-based platform designed to address these challenges by providing a mechanism for reproducible analysis of the Gaia archive data. There are two primary objectives of GAVIP. The first objective is to allow user-contributed algorithms, packaged as Added Value Interfaces (AVIs), to be executed near the Gaia archive so that data can be quickly acquired over internal network infrastructure. For example, it should be possible to package asteroid shape modelling code written in Fortran as simply as a stellar lightcurve classifier written in Java. The second objective is to allow users to easily use these AVIs, and share their results. The platform conceptually consists of four high-level elements: multiple AVIs; portal systems which provide the interface to the platform; AVI infrastructure to host AVIs; supporting systems. These elements are illustrated in Figure 1. The interrelationship of these elements, and a simplified view of the internal structure of an AVI can be found in Figure 2.

There are a wide range of requirements and diverse challenges involved in delivering such a platform, including interface, flexibility, performance and scalability requirements. Some of the most important requirements have been refined and provided in Table 1. A more detailed discussion of challenges in building the GAVIP platform is provided in this paper, setting the context for a detailed technical view of GAVIP and how it is designed to address these challenges. Related work is discussed in Section 2, providing an overview of related platforms and introducing one of the first design choices of GAVIP (virtualisation using Docker containers). The GAVIP concept is then presented in Section 3, including an overview of GAVIP operations and the key features of the platform. Next, Section 4 describes the architecture and technical implementation of the GAVIP platform. Finally, Section 5 contains the overall conclusions and offers suggestions for future work.

† http://www.nature.com/news/reproducibility-1.17552
Table 1: GAVIP Requirements.

| Requirement       | Description                                                                                                                                 |
|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Automation        | The GAVIP platform must be highly automated, requiring little to no operator intervention.                                                   |
| Web-based         | GAVIP users shall be able to completely interact with the platform and its AVIs using a web-browser.                                         |
| AVI flexibility    | Each AVI must be highly configurable by the user, including the arbitrary selection of input parameters.                                     |
| AVI isolation      | Following the GAVIP automation requirement, AVI submission must be automated, leading to the removal of manual code inspection. Individual AVI design may result in undesired behaviour when handling concurrent requests from multiple users. Therefore, AVIs must be isolated as far as possible. |
| Data sharing      | GAVIP shall facilitate across-AVI sharing of both inputs and outputs.                                                                           |
| Simultaneous usage| GAVIP must support the simultaneous execution of multiple AVIs (including multiple instances of the same AVI).                                |
| Scalability       | As the GAVIP community increases, and AVI pipelines become more complex, the platform must be able to scale in order to support growing demand.         |
| Load control      | GAVIP must provide functionality to prevent the capacity of the system being exceeded.                                                        |

2. RELATED WORK

In this section, related work to the GAVIP platform is discussed, focusing on similar platforms and services. Prior to this discussion, a brief introduction to the technical requirements of virtualisation and large scale data
2.1 Virtualisation Methods

One primary GAVIP requirement is AVI isolation (see Table 1). Two options were considered to achieve this, namely (1) Virtual Machines, and (2) operating system (OS) level virtualisation (containers). The latter was selected, implemented using Docker [10], principally due to the differences in resource usage between the two techniques. In the case of virtual machines, a hypervisor is used to emulate computer hardware which an operating system, libraries, and application must be installed on. However, with containers, a virtual environment is provided that shares the majority of the underlying operating system; this is illustrated in Figure 3. In addition to the reduced RAM footprint with container virtualisation, there is also an improvement in hardware utilization as the hardware (for example, the CPU or RAM) is directly accessed rather than being used through an emulator (the hypervisor).

Beyond the benefits in resource usage and utilisation, containers can be created and started much more quickly than virtual machines (often in under a second), as they share the majority of the host operating system. This gives GAVIP the ability to create and start AVIs on demand, for individual users. This ability to run containers on demand is used to support running AVIs in different modes of operation, which is one of the key techniques used to manage platform resources (see section 3.2.3). Containers also offer a unique level of application portability. This is especially useful when sharing applications within a community, as a container image can be copied and used to provide an exact copy of a software environment. In the case of GAVIP, it is crucial that this is the case, as astronomy software can rely on a wide array of packages, for example, NumPy [12] and SciPy [13] that require compilation for the environment in which they run.

2.2 Existing data analysis tools

A number of platforms have recently emerged that address some of the contemporary data analysis requirements. For example, the Google Cloud Datalab [14] provides a facility for hosting and running analysis tools on large data-sets. The challenge of general reproducibility of analysis and scientific experiments is a motivation for Binder [15]. Both of these platforms use a combination of OS virtualisation (for example, Docker) and Jupyter Notebooks [16] as part of their underlying technology. Within the astronomy community, there are a number of platforms which have been built to facilitate exploitation of astronomy data; for example, the Canadian Astronomy Data Centre (CADC - 17), and SciServer [18]. Both of these platforms offer users the ability to interact with large data sets, by running analysis within the platform’s infrastructure. The CADC platform provides a portal for several data-products, as well as services to interact with these data-products. While most of the services are online tools for data inspection, a “Virtual Machine on Demand” service is provided which
allows users to create batch processing jobs against data-archives. SciServer is a modular platform comprising of multiple components which allow users to perform complex queries on large databases, inspect the Sloan Digital Sky Survey, store data products, cross match astronomical datasets, and access SciServer services using Python, R, and Matlab scripts [19]. Both of these platforms have similarities with the GAVIP platform; they both allow users to perform remote analysis and store their data-products. However, their approaches to post processing of data-products are different. The SciServer platform provides an extensible range of tools, but they are developed within the platform, and can’t be provided by external users. CADC allows users to provide their own analysis tool (through “Virtual Machine on Demand”), but this is purely for executing a custom processing task. GAVIP provides a combination of these features, allowing users to provide their own tools (comprised of both processing jobs and interfaces), and easily share them within the platform for other users.

GAVIP uses Docker as its underlying container engine, and involves Jupyter as part of its recommended AVI development practices, similar to both Binder and Google Datalab. However, GAVIP also encourages the evolution of algorithms, often captured in notebooks, to form interactive web-tools packaged as AVIs. This design aids exposure of the data and its analysis as AVIs to the wider scientific community, without the need for programming expertise. The GAVIP concept is discussed further in Section 3 with the underlying architecture presented in Section 4.

3. GAVIP CONCEPT

As illustrated in Figure 1, GAVIP consists of a portal, AVIs, AVI infrastructure, and supporting systems used by the platform. The GAVIP portal provides the web interface to the platform, and is the central point of access for all platform users. The portal allows users to submit, browse, and execute AVIs, as well as inspect resulting data products. AVIs consist of a Docker container (referred to as the AVI container) running user-contributed code within the AVI framework. The user-contributed code, referred to as the AVI code, generally consists of a web interface and one or more pipelines. A pipeline is a set of tasks within an AVI that perform some level of analysis or further processing of the Gaia data archive, ultimately providing added value. Pipelines and interfaces of AVIs are decoupled within GAVIP to more cleanly separate the resource demands within the platform, as a web interface typically requires fewer resources in comparison to pipeline algorithms. Further detail on the platform architecture is provided in Section 4.

3.1 GAVIP User Roles

GAVIP defines four types of roles for registered users. Users may have more than one defined role. An additional role is used to define behaviour for anonymous users. Each of these roles are designed to satisfy different platform usage; their primary purposes are briefly described in Table 2.

| GAVIP Role    | Description                                                                 |
|---------------|-----------------------------------------------------------------------------|
| Operator      | Maintains and configures the system, including viewing and managing all con-  |
|               | tainer deployments as required.                                             |
| Developer     | Creates and submits AVIs to the GAVIP platform. Discussion of AVI develop- |
|               | ment scenarios are provided later in section 3.3                           |
| Scientist     | Browses the AVI catalogue within GAVIP, starts and uses AVIs.               |
| Outreach user | Can browse and interact with AVIs similar to Scientists, but is offered alter- |
|               | native interfaces for simpler interaction with the archive, for the sake of outreach. |
| Anonymous user| Can browse and interact with AVIs similar to Scientists, but is restricted by the amount of resources that may be consumed in doing so. |

Table 2: GAVIP User Roles.

3.2 GAVIP Features

An overview of the high-level features in GAVIP can be found in Table 3. These features have been derived from the requirements in Table 1. They are further described in more technical detail in Section 4.
**Table 3: GAVIP features**

| Feature                  | Overview                                                                                                                                                                                                 |
|--------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| AVI framework            | The AVI framework provides the foundation for AVIs and is used to convert an algorithm into a reusable and shareable tool.                                                                                 |
| User-space               | The user-space is a persistent storage volume that is accessible by all AVIs. The platform includes a browser for the user-space.                                                                        |
| Data-sharing             | To minimize unnecessary processing of data, users can share data products. Other users can reuse these data products in their AVIs.                                                                         |
| Dashboard                | A dashboard is provided in GAVIP to enable simultaneous interaction with multiple AVI interfaces.                                                                                                       |
| Command Line Interface (CLI) | A CLI to the platform is provided by the GAVIP client.                                                                                                                                                   |
| AVI Development          | AVI development is the process of creating an AVI outside of the platform in “standalone” mode, and submitting it to the platform when ready. This process has been designed to be relatively simple, non-restrictive, while also ensuring compatibility with the GAVIP platform. See section 3.2.2 for more detail. |

GAVIP is designed for use on a data archive which is itself scheduled for full release years after the platform is completed. One of the driving challenges of GAVIP is providing a platform that will not become obsolete before the data archive is fully available. AVIs are ultimately what will attract users to the GAVIP platform; the value of the platform from the scientific community’s perspective is provided only by AVIs. Three exemplar AVIs are currently under development, and will be deployed in GAVIP prior to public release of the full archive. However, the GAVIP ecosystem must expand for the platform to reach its full potential. This introduces the challenges associated with the AVI framework (3.2.1). Beyond the design of the framework, there are also challenges in how AVIs are developed (3.2.2). Once AVIs are functional and simple to develop, management of AVI resources leads to the majority of the challenges in GAVIP (3.2.3).

### 3.2.1 The AVI framework

The AVI framework is implemented within AVI containers, and provides the infrastructure and much of the boilerplate functionality required for an AVI. This framework must be:

1. Able to support the queueing and execution of complex pipelines against the Gaia data archive;
2. Flexible so that developers can use tools and libraries not yet released;
3. Easy to use, as AVIs will not be developed if the process is too complex.

At a high level, the AVI framework is implemented as a web application using the Django web framework [20]. The AVI created by developers forms one component or “application” which is run within the AVI framework. The framework handles pipeline management, GAVIP communications, and authentication with GAVIP. In addition, the framework supports standalone operation for development purposes. See section 4.3.1 for detail on the AVI structure.

### 3.2.2 AVI development

AVI development involves developing an AVI locally, and submitting it for deployment within GAVIP. This is achieved by running AVIs (Docker containers) in ‘standalone’ mode on the developers machine. The container images used within GAVIP are publicly available for download, and allow developers to replicate the expected AVI environment with certainty. While running in this mode the AVI mounts code which is initially cloned from one of many example AVIs [21] provided with GAVIP. Once the developer is satisfied with their AVI, they simply save the changes and upload their AVI code to the platform (the AVI container used locally is not required). Further detail on the AVI development process is available in section 4.3.3.
3.2.3 Resource management

AVIs are designed to run at a large archive in excess of 1 PB in size; as such it is expected that AVIs may often require significant resources to operate. In addition, AVI resources must be isolated so that they do not impact other AVIs, or indeed the platform, and cannot gain undesired access to another users data-products. GAVIP must also support hundreds of simultaneous users. These requirements provide a significant challenge for any platform, but due to the requirements of GAVIP, there is another layer to the complexity of resource management. AVIs provide a web interface, and serving hundreds of requests is a simple task for any web application. However, as AVIs must only be able to interact with data from the ‘owner’ (the user who wishes to interact with the AVI), they must be provided for one unique user at a time. GAVIP satisfies these requirements by creating and running AVIs on demand, and again leveraging the ability for AVIs to operate in different modes. The ability to create and run AVIs on demand is made possible by the underlying use of containers rather than virtual machines.

As described previously in this section, AVIs separate interfaces from pipelines in the interest of separating the demands of system resources. In the case of AVI web interfaces, the AVI is started on demand by a user selecting an AVI from a catalogue. The AVI is provisioned with hundreds of megabytes of RAM, and destroyed when not in use (determined by the user signing out, or session expiring). The expected RAM requirements of AVI pipelines will generally surpass the hundreds of megabytes with which AVI interfaces are executed. Consequently, when a user attempts to invoke a pipeline, the AVI framework automatically dispatches a job request (referred to as an AVI task). AVI containers are started in order to process these job requests, and are dynamically allocated RAM depending on the unique requirements of each job. This allows AVI developers to, if they wish, provide an algorithm to determine the RAM to be allocated for a particular job, or suggest a RAM allocation to a user, or even allow the user to specify it directly. Considering the context of AVIs and the freedom afforded to developers, this is a significant feature of the platform; it enables developers to write arbitrarily complex processes as pipelines and dynamically request the resources to run them, all supported within shared infrastructure.

To ensure that GAVIP resources are not over-allocated, AVI pipelines are not started immediately; rather they are managed by a scheduler. The scheduler monitors various metrics of the platform including GAVIP resources, job submission time, jobs submitted per user, and begins an AVI pipeline when appropriate. An AVI pipeline is executed in a separate container to the AVI interface, but they are structured identically; the most significant differences are resource allocations and the processes they are running. Ultimately, the solution to resource management within GAVIP is to allow AVIs to run in different modes, run complex processing tasks with dynamically allocated resources, and defer those tasks until possible for safe execution.

4. ARCHITECTURE

Generally, GAVIP is implemented in Python, apart from Consumer Off The Shelf (COTS) components such as RabbitMQ [22]. All background processes and web interfaces are Python-based. Docker is used as GAVIP’s container system, with Docker Swarm employed to provide a scalable Docker system across multiple servers.

4.1 High-Level Architecture

The GAVIP platform consists of four high-level elements that are listed below with a brief description of their purpose. These elements are illustrated in Figure [1]

1. Portal interfaces: These allows users to interact with the platform, and access AVIs.
   (a) Graphical user interaction: Users are able to interact with the GAVIP platform through a graphical web interface rendered in a web-browser.
   (b) Programmatic user interaction: The API provided by the portal is generally exercised through the graphical web interface. However, GAVIP was designed to support programmatic interaction, allowing the platform to be integrated with other scripts or existing tools. As such the API is RESTful, and can already be easily integrated with tools such as the provided GAVIP client.
2. **AVI Infrastructure**: Hosts and controls AVI containers.

   (a) The AVI infrastructure is remotely commanded by the Portal component. It performs operations such as creating, querying, updating, and deleting the Docker containers which are used to execute AVIs.

3. **AVI**: user-defined algorithms and interfaces hosted in Docker containers. The different modes of AVI operation are outlined below with a description (previously discussed in section 3.2.3).

   (a) **Standalone**: The AVI operates on a developer’s machine providing limited functionality within a replica of the deployed AVI environment. Resources are not restricted. Any jobs triggered through the AVI are executed asynchronously within the same container.

   (b) **AVI Interface deployment**: The AVI is deployed within the AVI infrastructure of GAVIP. It is allocated a few hundred megabytes of RAM (≈200MB) for operation. Any jobs triggered through the AVI are queued and scheduled in GAVIP.

   (c) **AVI Pipeline deployment**: The AVI is deployed within the AVI infrastructure of GAVIP. It is deployed with a configurable allocation of resources. It does not provide any interface, and is configured to run a single task; the container is destroyed when the task is completed.

4. **Supporting Systems**: miscellaneous components, employed by the core functionality of the system.

   (a) The supporting systems consist of miscellaneous software that may be integrated with other components, such as the message bus and monitoring service.

4.2 **Component Level Architecture**

The four high-level elements of GAVIP can be further sub-divided into 13 components, listed below with a short description. An illustration of these 13 components is provided in Figure 4.

![Figure 4: GAVIP component overview showing the 13 main components and their parent high-level elements.](image-url)
4.2.1 Portal Web System

The web system provides a RESTful API with a graphical web-interface for users to interact with the GAVIP platform. It is built using Django [20], the Django Rest Framework [23], and Swagger [24]. The latter is used to build API documentation from the interfaces defined using the Django Rest Framework. The data generated by Swagger is used by the GAVIP client (section 4.2.13) to dynamically construct its CLI.

4.2.2 Portal Authentication/Authorisation

This component handles authentication of users within GAVIP. Authentication is offloaded to a (Central Authentication Service) CAS server by the django-cas plugin. By offloading to a CAS server, passwords need not be stored in the platform, thus reducing security concerns. A local CAS server is used during GAVIP development; once deployed in ESAC infrastructure, GAVIP will use ESAC’s CAS server.

4.2.3 Messaging

The GAVIP platform consists of many components which each often have associated tasks which must be executed, usually in a background process. For example, the virtualization controller has many deployment tasks for different types of containers. RabbitMQ is used to provide a message bus for GAVIP components to communicate. Celery is used to provide a powerful interface to RabbitMQ. By designing GAVIP around a message bus, complex orchestration tasks are easier to control. For example, an outline of the AVI pipeline deployment process is as follows:

1. Preparing the user-space.
2. Downloading the AVI code.
3. Preparing a queue on the message bus, which is used to send a single job to the AVI.
4. Starting the container.
5. Stopping the container once the job is complete.

Some of these tasks may occur within different servers in the platform.

4.2.4 Repository

The code for each AVI is maintained within GAVIP using a Git repository. A developer is allocated an individual repository for each AVI they develop. By default, these repositories are private to encourage development and use of tools without exposing source code, but may optionally be exposed publicly.

4.2.5 AVI Web System

Provides the web-interface, built using Django. Other AVI components such as the AVI pipeline and AVI authentication systems are integrated through this Django web application. AVI developers provide one (Django) app, a single subdirectory within this Django project that is automatically integrated into other components such as the pipeline system (the latter is described in more detail in Section 4.2.6).

4.2.6 AVI Pipeline system

Provides the framework for easily submitting and executing pipelines (long running processes) as asynchronous jobs. Pipelines are built and defined by code using Luigi. Although the pipeline framework is written in Python, the AVI framework supports executing Java or Fortran code, which can be called within the pipeline. Using the pipeline system is mostly automatic and requires little development effort:

1. Build a pipeline with the required arguments.
2. Build a Django model that includes those arguments, extending the AviJob model.
3. Create a Django view which saves an instance of the model (for example, through a form submission).
All queueing and job submission occurs automatically using hooks in the `save()` functions of the `AviJob` model. Each `AviJob` automatically includes fields for specifying the resource requirements for each job. Furthermore, each `AviJob` has an associated pipeline state model which stores the progress and state of each job. The pipeline state information is used within the platform to build interfaces such as progress bars. The progress of each job is calculated using the total number of required tasks, and number of completed tasks in a pipeline. Luigi is used for building pipelines in the AVI, and determines these numbers within the framework. Luigi also provides event hooks which are used for updating the job progress.

4.2.7 AVI Authentication/Authorisation

AVI authentication uses OAuth 2.0 [25, 26] to authenticate a user within GAVIP. The platform returns a description of the user and their roles (user profile) to the AVI. The user profile is used for authorisation functionality that permits AVI behaviour to be modified based on user roles within GAVIP. For example, alternative AVI interfaces may be provided to outreach users. The platform uses the `oauth2_provider` [27] plugin for Django.

4.2.8 Connectors/Services

Connectors and services are reusable libraries available within the AVI framework. ‘Connectors’ provide interfaces to thirdparty systems such as Gaia Archive Core Systems (GACS). ‘Services’ are sets of pipeline operations that may be easily integrated in any AVI pipeline, typically using one or more connectors to provide common operations. One example of a connector currently provides a TAP+ interface. In contrast, a service would use the TAP+ connector to submit, monitor, and download the results of an asynchronous Astronomical Data Query Language (ADQL) [28] job.

4.2.9 Virtualisation Management

Manages autonomous deployment of AVIs, minimizing the need for operator intervention; ultimately this component allows containers to be rapidly started on demand. It uses the Python Docker client (`docker-py`), and connects to a local port that exposes either the standard Docker engine or Docker Swarm. It is composed of a set of asynchronous tasks for deploying containers, classes which generate the configuration for different types of containers, and Django views which provide an API for interfacing with the controller.

4.2.10 AVI Scheduler

Schedules the execution of AVI pipelines with custom resource allocations to manage system load. Each scheduler implements a class containing a function that determines the next AVI task to be executed. Multiple classes with different scheduling algorithms will be developed and can be selected in the GAVIP platform settings.

4.2.11 User-space

Provides a persistent storage system for each user. The user-space is currently implemented as an NFS volume (though this is subject to change). Alternative methods of user-space storage may be object bases (similar to Amazon S3). Docker can be extended to use alternative storage engines through its plugin system. All AVIs started by each user will be configured to mount their unique user-space for reading and writing data products. A user-space browser is included in the portal web system that enables users to browse, upload, download, and delete the corresponding files.

4.2.12 Monitoring

GAVIP components, including AVIs, are monitored by Zabbix [29], which provides a web dashboard similar to Nagios [30] and Munin [31].
4.2.13 GAVIP client

Provides a command line interface to GAVIP, permitting almost all platform operations to be invoked program-
matically without the need for a web browser. Additional commands for AVI development are included in the
client that invoke Docker commands on the local machine. For example, a quickstart command is provided
that downloads, prepares, and starts an example AVI [21]. Although Docker is run on Linux and currently
requires a Virtual Machine to run on Windows or MacOS systems, native solutions are being developed which
will remove this requirement [32]. The GAVIP client is built using the Python click module. The algorithm
which parses the platform API and generates the CLI commands (via data provided by Swagger in the Portal
web system) was developed internally.

4.3 Feature Implementation

4.3.1 AVI structure

The AVI structure is described here to provide context for subsequent sections. An illustration of the AVI
structure including the applications within the AVI Framework can be seen in Figure 5. The green box labelled
“Shared Volume” represents the mounted user-space directory, where the AVI stores persistent data-products.
The two purple boxes labelled “Web Server” and “AVI Worker” represent two modes of operation for the AVI
framework; the former provides a web interface for using the AVI, while the latter processes a single AVI job.
AVI jobs are created by users interacting with the interface and submitting jobs to the GAVIP platform, or to
an internal worker when running in “standalone” mode. A description of each of the framework applications is
provided in Table 4. The AVI framework also provides a wide array of installed packages available for use (by
including an Anaconda bundle), for example:

- astroML (v0.3)
- astropy (v1.1.2)
- astroquery (v0.3.1)
- blaze (v0.9.1)
- bokeh (v0.11.1)
- dask (v0.8.1)
- Jinja2 (v2.8)
- lxml (v3.6.0)
- matplotlib (v1.5.1)
- numba (v0.24.0)
- numexpr (v2.5)
- numpy (v1.10.4)
- pandas (v0.18.0)
- pandas-profiling (v1.0.0a2)
- psycopg2 (v2.6.1)
- pyfits (v3.4)
- scikit-image (v0.12.3)
- scikit-learn (v0.17.1)
- scipy (v0.17.0)
- seaborn (v0.7.0)
- statsmodels (v0.6.1)

Figure 5: Internal AVI illustration, consisting of the AVI framework executing the avi code provided by a
developer. The AVI framework is running in a container that is based on one of the provided AVI templates.
Two modes of operation are shown for the AVI framework (‘Web Server’ and ‘AVI Worker’). When the AVI is
running a ‘Web Server’, it exposes a HTTP interface to the AVI. Alternatively, when running an ‘AVI Worker’,
it processes a single AVI job (an AVI pipeline).
| Application | Description |
|-------------|-------------|
| avi         | Code written by the AVI developer. It will typically include model definitions, Django views, URLs, and HTML templates. |
| avi_auth    | Handles authenticating the AVI within the platform. OAuth is used as the AVI cannot access the GAVIP database. GAVIP returns a user profile object which contains details of the user. |
| base        | Contains base HTML for providing a consistent look and feel to the AVI. |
| gavip_avi   | The root Django application which defines the installed applications, root URL structure, and configuration of the AVI. |
| connectors  | Python interfaces for IVOA protocols. See Section [4.2.8](#). |
| services    | Pipeline tasks which implement some usage of a connector. For example, a ‘GACS’ service is provided which uses the TAP+ connector to manage a job from GACS. See Section [4.2.8](#). |
| plugins     | Provides reusable Django views to reduce web development effort required by AVI developers. |
| pipeline    | Includes the classes, event handlers and tasks required for managing AVI jobs. |

Table 4: AVI Framework Applications.

### 4.3.2 AVI pipelines

AVI pipelines are used to execute all long-running processes within an AVI. Pipelines are implemented using a combination of Luigi [33] and Celery [34]. Luigi allows pipelines to be defined by code. Celery is used to manage queueing of asynchronous jobs. A sample Luigi task can be seen in Figure 6 with a short sample AVI pipeline shown in Figure 7 (note that the code is collapsed in these figures for brevity). Each task of an AVI pipeline (e.g. DownloadData and ProcessData in Figure 7) are inspected before execution to see if the output defined by the step already exists. If this is true, the task is skipped. This allows developers to easily prevent unnecessary computation (for example, a task output file may be constructed using a hash of the corresponding input parameters).

![Figure 6: A sample Luigi task showing how the pipeline structure is defined by code by explicitly defining parameters and using requires(), run() and output() functions. Source: Luigi documentation [35](#).](image)
Figure 7: A screenshot of a sample pipeline showing two tasks `DownloadData` and `ProcessData`. The classes `AviTask`, `AviParameter`, and `AviLocalTarget` are all extensions of Luigi classes. The `DownloadData` task extends the service class `services.gacs.GacsQuery`, which itself is an `AviTask`. In this example, `GacsQuery` implements the `run()` function that will be used during the execution of the `DownloadData` task, thus demonstrating how services can be used to include common functionality in AVI pipelines.

Once a pipeline is created in the AVI framework, a model (Django model) must be created to store the associated arguments for the pipeline. The job request handled by Celery only requires the primary key of the model instance rather than all the arguments to the pipeline. This simplifies the Celery message content, and bypasses the need for serializing complex objects such as input files. The model created by the developer extends a model class provided by the framework called `AviJob`. The `AviJob` model provides logic for creating the AVI job request and submitting it to the portal. Once the model is saved (e.g., upon a form submission in the AVI), a task is submitted for processing. As described in Section 4.3.6, AVIs have different modes of operation so that resources can be allocated when required. AVIs may run on a developers machine in “standalone” mode or may run within the GAVIP platform (either to provide a web interface or process a single AVI job). No further development is required by developers to support these different modes of operation; decoupling of AVI behaviour happens automatically, and is part of the logic provided by the `AviJob` model.

4.3.3 AVI development

The AVI development process is described in this section, with prerequisite information regarding AVI images and development environment provided beforehand.

**AVI template** Before an AVI is developed, a GAVIP operator must make one or more “AVI templates” available. These are Docker images built for the platform, and provide an image from which AVI containers are created. A list of some of the available images can be found in Table 5. These images may be downloaded from [https://repositories.gavip.science](https://repositories.gavip.science) using the associated image identifiers, which are distributed in the GAVIP Developer manuals that are provided with each release of the platform. Additional AVI templates will be provided at a later date to support the use of additional languages such as Fortran.
**Table 5: AVI Templates.**

| Template     | Description                                                                 |
|--------------|-----------------------------------------------------------------------------|
| Python AVI   | It includes all components required to execute either an AVI web interface or AVI pipeline. |
| Java (7) AVI | An extension of the Python AVI template, which permits the execution of AVIs that have Java (7) dependencies. |
| Java (8) AVI | An extension of the Python AVI template, which permits the execution of AVIs that have Java (8) dependencies. |

**AVI project** AVIs are created in GAVIP using an “AVI template” and a particular release version of an “AVI project”. An AVI project is a record consisting of a particular Git repository (which hosts the AVI code), and some metadata such as AVI title and author. An AVI release is a record which provides a snapshot of the AVI project repository. The record consists of a Git hash (a unique identifier for each change to the repository), a version number, and a flag indicating whether the release is to be public or not. If the release is not made public, it will only be made available to the AVI developer rather than all users of the platform.

**Development environment** A developer guide is provided by GAVIP to help users create AVIs. The guide includes a list of prerequisite requirements including particular packages, with Docker and the GAVIP Client being two key examples of the latter. Docker is used to run the AVI in ‘standalone’ mode on the developers machine during development, while the GAVIP client automates some of the interactions with both the GAVIP platform and Docker for the sake of convenience.

**Development process** AVIs will typically begin with a concept algorithm to form the basis of the AVI. Developers are encouraged to use a Jupyter notebook (hosted within GAVIP) to prototype an algorithm before AVI development. For more information on the execution of Jupyter notebooks in the platform, refer to section 4.3.4. AVI developers will follow the AVI development guide provided by GAVIP. As part of this, they set up any prerequisites such as Docker and the GAVIP client. The development process is outlined in Figure 8. When a developer creates a public AVI release, the AVI is immediately available within the GAVIP platform for other users to use.

### 4.3.4 Jupyter notebooks

Jupyter notebooks can be executed within GAVIP by any user. They are started in an isolated container built from the Python AVI template; this permits a notebook to import and use features within the AVI framework (e.g. the TAP+ connector). The notebooks are saved in the user-space, and can be downloaded using the user-space browser.

### 4.3.5 Dashboards

The GAVIP portal provides a unique interface that permits multiple AVIs to be simultaneously viewed and dynamically rearranged and resized by the user. The dashboard is implemented using Gridster [36] and HTML Iframes. Gridster is used as it enables HTML `<div>` tags to be resized and repositioned within a web page. HTML Iframes permit AVI views to be loaded within these `<div>` tags. A SAMP Hub is available for each user of GAVIP, and is intended to provide a means of communication between multiple AVIs. Other tools such as TopCat may be connected to the GAVIP SAMP hub, which would require the use of a proxy using the SAMP web profile. The AVI framework includes a “plugin” which can be used in any of the AVI web pages to initialize and expose a SAMPJS connector to the user’s SAMP hub.

Users may add and remove AVI views from their dashboard as they wish. If an AVI is not running, and is required by the dashboard, it is created and started (this process takes the order of seconds). A catalogue of AVI views will be provided for the user when they wish to add a new view. It is expected that these views will be identified when an AVI is submitted to GAVIP through a naming convention (e.g. `dashboard.3d.star_plot()`); this is yet to be finalized. Each user may save arrangements of AVI views within the dashboard as “dashboard...
presets”. Developers can also create “dashboard presets”, and these are made available to all users. These presets are persisted as records within the GAVIP database.

4.3.6 Resource management

GAVIP resource management involves recording the following:

- Resources required for different processes.
  - For example, the resources required by a container running an AVI interface or pipeline.
- Total resources currently allocated per user.
- Maximum allocation of resources per user at any instant.

Each user is assigned a limit to the amount of resources they can have allocated at any point in time; this is known as a resource pool. The resource pool is used to inform the user, and help the user consider that certain operations require resources in the platform. All containers used within GAVIP extend a GavipContainer class, which has attributes used for recording the resources to be allocated to that container. For most containers, these values are read from a configuration file. However, for containers running AVI pipelines, they are read from the associated AVI job (sent by the AVI). The AviJob model provided in the AVI framework contains fields for storing the resources to be allocated when running the pipeline. As this is stored in the AviJob model, it may be modified by the developer or by the user as appropriate, depending purely on the algorithm being used and
structure of the pipeline. Occasionally, a resource-intensive portion of the pipeline is skipped as the output file has already been created (see Section 4.3.2).

When a container is being started (e.g. an AVI pipeline container, or AVI interface container) the resources required are checked against the free resources available (determined by subtracting the allocated resources from the resource pool). Every container used in GAVIP has an associated model that is used to track all container deployments. Whenever the container model is saved, the allocated resources are recalculated.

4.3.7 GAVIP client
The GAVIP client provides a command line interface to the GAVIP platform, and assists AVI development. It is built using Click [37]. The commands in the client are dynamically generated by parsing API documentation hosted by the GAVIP platform. This API documentation is provided by Django-Rest-Swagger [24] working with the Django Rest Framework [23] and is hosted within the portal. Django-Rest-Swagger is a Django plugin that provides Swagger API documentation. As part of this process, a hierarchical data representation of the API is made available which details:

- The URL of a particular view.
- A function nickname.
- Documentation from the function docstring.
- Input parameter details (including parameter type where possible).
- Output parameter details.

When a user logs in to the GAVIP platform using the client, this API is read and used to dynamically generate and decorate functions which interact with the GAVIP platform. The Click module includes an autocomplete function that works with these generated functions. A demo of API generation can be viewed online‡.

5. CONCLUSIONS AND FUTURE WORK
The GAVIP platform is designed to enable communities to incorporate existing codes and develop an expanding repository of tools to engage with large data-archives (the Gaia data archive in this case) without requiring the archive to be downloaded. There are many related and driving requirements behind the design of GAVIP, some of which have been refined in Table.⁠§ GAVIP is required to be highly automated, able to run multiple AVIs in isolation, and dynamically control the demands on system resources. By using containers to host AVIs, we have maximized the isolation of AVIs while minimising the resources required to do so. Designing AVIs such that they have different modes of operation allows the demands on system resources to be decoupled and managed separately. Combined, these two features allow the platform to meet automation, isolation, scalability, and load control requirements. The AVI framework is designed to meet the requirements of AVI flexibility and web-based interaction by supporting developers in creating complex pipelines with few restrictions, and interfaces using the latest web-technologies, as well as providing an expanding range of libraries and packaged utilities such as “Connectors” and “Services” (see Section 4.2.8). More generally, the platform also provides a mechanism for addressing the contemporary issue of scientific experiment reproducibility. In addition, the proposed design and implementation mean that it is suitable for use in domains beyond astronomy.

The Gaia archive data will be made available in multiple releases, where early releases will consist of restricted subsets of validated data with the individual epoch observations and transits appearing only in the final release. (an overview of the release scenario can be found online§). The GAVIP platform is scheduled for early deployment toward the end of 2016, potentially overlapping with the first Gaia data release. Final acceptance of GAVIP is scheduled for Q3 of 2017, potentially overlapping with the second of the five expected Gaia data releases. Three exemplar AVIs (GAVITA, GAVISC, and GAVIDAV) are being developed in tandem with GAVIP to be

‡ https://asciinema.org/a/44809
§ http://www.cosmos.esa.int/web/gaia/release
deployed within the platform prior to final acceptance. The first of these AVIs, GAVITA will provide added value in the domain of transient analysis (specifically, supernovae analysis). GAVITA is developed by Parameter Space in tandem with GAVIP; this helps establish an internal feedback loop of requirements and features of the platform. GAVISC will model and analyse asteroids detected by Gaia using a combination of Python and Fortran. GAVIDAV will provide a suite of visualisation tools which can be used on the Gaia archive, as well as data-products created by users in the platform. These AVIs will be installed and available within GAVIP before final acceptance of the platform.

As part of GAVIP development and design, additional features of the platform have been identified that will be researched in the future, for example, the compute power available to AVIs. Currently, AVI pipelines run solely within a Docker container using resources from the host system, rather than being run on a compute cluster such as Apache Hadoop [38]. Although not all AVIs will require a compute cluster, access to such a facility will enhance the potential impact of the platform. The platform is technically capable of exploiting a compute cluster, as the software used to define pipelines with the AVI framework (Luigi) already supports the integration of separate Apache Hadoop or Apache Spark [39] clusters. Other GAVIP modifications for cluster integration include extension of the existing resource pool implementation to interact with the cluster’s own resource manager, for example Apache Hadoop YARN [40], and managing user behaviour to prevent unnecessary usage of the cluster for trivial jobs. It is intended that compute cluster integration will be formally included in future releases of GAVIP.

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