Replica Management in the European DataGrid Project †

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Abstract.

Within the European DataGrid project, Work Package 2 has designed and implemented a set of integrated replica management services for use by data intensive scientific applications. These services, based on the web services model, enable movement and replication of data at high speed from one geographical site to another, management of distributed replicated data, optimization of access to data, and the provision of a metadata management tool. In this paper we describe the architecture and implementation of these services and evaluate their performance under demanding Grid conditions.

1. Introduction

The European DataGrid (EDG) project was charged with providing a Grid infrastructure for the massive computational and data handling requirements of several large scientific experiments. The size of these requirements brought the need for scalable and robust data management services. These services had to manage replication of large amounts of data across wide area networks and provide transparent access to distributed storage systems holding this data. Creating these services was the task of EDG Work Package 2 (WP2).

The first prototype replica management system was implemented early in the lifetime of the project in C++ and comprised the edg-replica-manager [24], based on the Globus toolkit, and the Grid Data Mirroring Package (GDMP) [25]. GDMP was a service for the replica-

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tion (mirroring) of file sets between Storage Elements and together with the edg-replica-manager it provided basic replication functionality.

After the experience gained from deployment of these prototypes and feedback from users, it was decided to adopt the web services paradigm [31] and implement the replica management components in Java. The second generation replica management system now includes the following services: the Replica Location Service, the Replica Metadata Catalog, and the Replica Optimization Service. The primary interface between users and these services is the Replica Manager client.

In this paper we discuss the architecture and functionality of these components and analyse their performance. The results show that they can handle user loads as expected and scale well. WP2 services have already been used as production services for the LHC Computing Grid [22] in preparation for the start of the next generation of physics experiments at CERN in 2007. A "data challenge" run by the CMS experiment from March to May 2004 successfully used the Replica Location Service to store and query information on over two million replicated data files.

The paper is organised as follows: in Section 2 we give an overview of the architecture of the WP2 services and in Section 3 we describe the replication services in detail. In Section 4 we evaluate the performance of the replication services and Section 5 discusses directions of possible future work. Related work is described in Section 6 and we conclude in Section 7.

2. Design and Architecture

The WP2 replica management services [10, 20] are based on web services and implemented in Java, adhering to the following principles:

- Modularity: Replica management components were designed to be modular so that plug-ins and future extensions are easy to apply and each service can operate independently of the others.
- Evolution: The future directions and standards for Grid services are not well defined, but several groups are working to implement a framework for Service Oriented Computing [17, 18]. The replica management components were designed to be flexible with repsect to these evolving areas and the design allowed for an easy adoption of these concepts.
- Deployment: A vendor neutral approach was adopted for all components to allow for different deployment scenarios. The data man-

agement services are independent of the underlying operating system and have been tested on Tomcat and the Oracle 9i Application Servers, interfacing to MySQL and Oracle database back-ends.

2.1. Web Service Design

Web service technologies [31] provide an easy and standardized way to logically connect distributed services via XML (eXtensible Markup Language) messaging. They provide a platform and language independent way of accessing the information held by the service and, as such, are highly suited to a multi-language, multi-domain environment such as a DataGrid.

All the replica management services have been designed and deployed as web services and run on Apache Axis [4] inside a Java servlet engine. All services use the Java reference servlet engine, Tomcat [5], from the Apache Jakarta project [28]. The Replica Metadata Catalog and Replica Location Service have also been successfully deployed into the Oracle 9i Application Server and are being used in production mode in the LCG project [22].

The services expose a standard interface in WSDL format [32] from which client stubs can be generated automatically in any of the common programming languages. A user application can then invoke the remote service directly. Pre-built client stubs are packaged as Java JAR files and shared and static libraries for Java and C++, respectively. C++ clients are built based on the gSOAP toolkit [29]. Client Command Line Interfaces are also provided.

The communication between the client and server components is via the HTTP(S) protocol and the data format of the messages is XML, with the request being wrapped using standard SOAP Remote Procedure Call (RPC). Persistent data is stored in a relational database management system. Services that make data persistent have been tested and deployed with both open source (MySQL) and commercial (Oracle 9i) database back-ends, using abstract interfaces so that other RDBMS systems can be easily slotted in.

3. Replication Services

The design of the replica management system is modular, with several independent services interacting via the Replica Manager, a logical single point of entry to the system for users and other external services. The Replica Manager coordinates the interactions between all components of the system and uses underlying file transport services

for replica creation and deletion. Query functionality and cataloging are provided by the Replica Metadata Catalog and Replica Location Service. Optimized access to replicas is provided by the Replica Optimization Service, which aims to minimize file access times by directing file requests to appropriate replicas.

The Replica Manager is implemented as a client side tool. The Replica Metadata Catalog, Replica Location Service and the Replica Optimization Service are all stand-alone services, allowing for a multitude of deployment scenarios in a distributed environment. One advantage of such a design is that if any service is unavailable, the Replica Manager can still provide the functionality that does not make use of that particular service. Also, critical service components may have more than one instance to provide a higher level of availability and avoid service bottlenecks.

The downside is that a lot of the coordinating logic happens at the client side so asynchronous interaction is not possible. In cases of failure on the client side, the user is left with little possibility to automatically re-try the operations he has to deal with these cases himself. Before a Replica Management Service could be provided we would need a secure fine-grained delegation mechanism by the means of which the client could safely request the service to perform a well defined limited set of tasks. Full delegation is available but this gives little advantage over simple authentication which is built into the services already.

3.1. Replica Manager

For the user, the main entry point to the Replication Services is through the Replica Manager client interface that is provided via C++ and Java APIs and a command line interface. The actual choice of the service component to be used can be specified through configuration files. Java dynamic class loading features are exploited to make them available at execution time in the Replica Manager.

The Replica Manager also calls upon services external to WP2. An Information Service such as MDS (Monitoring and Discovery Service) or R-GMA (Relational Grid Monitoring Architecture) needs to be present, as well as storage resources with a well-defined interface, in our case SRM (Storage Resource Manager) or the EDG-SE (EDG Storage Element). The Replica Manager also makes use of transport mechanisms such as GridFTP.

3.2. Replica Location Service

In a highly geographically distributed environment, providing global access to data can be facilitated via replication, the creation of remote

read-only copies of files. In addition, data replication can reduce access latencies and improve system robustness and scalability. However, the existence of multiple replicas of files in a system introduces additional issues. The replicas must be kept consistent, they must be locatable and their lifetime must be managed. The Replica Location Service (RLS) is a system that maintains and provides access to information about the physical locations of copies of files [13].

The RLS architecture defines two types of components: the Local Replica Catalog (LRC) and the Replica Location Index (RLI). The LRC maintains information about replicas at a single site or on a single storage resource, thus maintaining reliable, up to date information about the independent local state. The RLI is a (distributed) index that maintains soft collective state information obtained from any number of LRCs.

Globally Unique IDentifiers (GUIDs) are 128-bit numbers used as guaranteed unique identifiers for data on the Grid. In the LRC each GUID is mapped to one or more physical file names identified by Storage URLs (SURLs), which represent paths to the physical locations of each replica of the data. The RLI stores mappings between GUIDs and the LRCs that hold a mapping for that GUID. A query on a replica is a two stage process. The client first queries the RLI in order to determine which LRCs contain mappings for a given GUID. One or more of the identified LRCs is then queried to find the associated SURLs.

An LRC is configured at deployment time to subscribe to one or more RLIs. The LRCs periodically publish the list of GUIDs they maintain to the set of RLIs that index them using a soft state protocol, meaning that the information in the RLI will time out and must be refreshed periodically. The soft state information is sent to the RLIs in a compressed format using bloom filter objects [9].

An LRC is typically deployed on a per site basis, or on a per storage resource basis, depending on the site's resources, needs and configuration. A site will typically deploy 1 or more RLIs depending on usage patterns and need. The LRC can also be deployed to work in stand-alone mode instead of fully distributed mode, providing the functionality of an replica catalog operating in a fully centralized manner. In stand-alone mode, one central LRC holds the GUID to SURL mappings for all the distributed Grid files.

3.3. Replica Metadata Catalog Service

The GUIDs stored in the RLS are neither intuitive nor user friendly. The Replica Metadata Catalog (RMC) allows the user to define and store Logical File Name (LFN) aliases to GUIDs. Many LFNs may

exist for one GUID but the LFN must be unique within the RMC. The relationship between LFNs, GUIDs and SURLs and how they are stored in the catalogs is summarised in Figure 1.

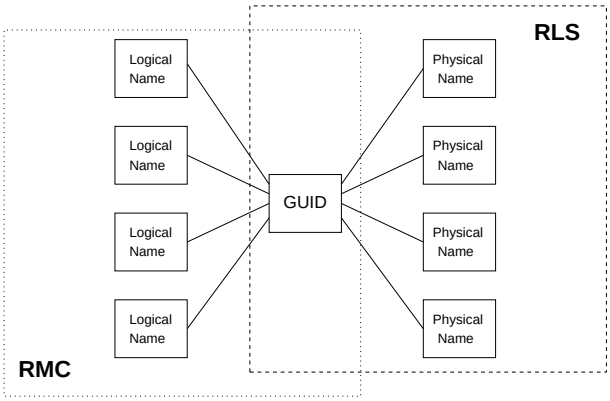

Figure 1. The Logical File Name to GUID mapping is maintained in the Replica Metadata Catalog, the GUID to physical file name (SURL) mapping in the RLS.

In addition, the RMC can store GUID metadata such as file size, owner and creation date. The RMC is not intended to manage all generic experimental metadata, however it is possible to extend the RMC to maintain O(10) items of user definable metadata. This metadata provides a means for a user to query the file catalog based upon application-defined attributes.

The RMC is implemented using the same technology choices as the RLS, and thus supports different back-end database implementations, and can be hosted within different application server environments.

The reason for providing a separate RMC service from the RLS for the LFN mapping is the different expected usage patterns of the LFN and replica lookups. The LFN to GUID mapping and the corresponding metadata are used by the users for preselection of the data to be processed. However the replica lookup happens at job scheduling time when the locations of the replicas need to be known and at application runtime when the user needs to access the file.

3.4. Replica Optimization Service

Optimization of the use of computing, storage and network resources is essential for application jobs to be executed efficiently. The Replica Optimization Service (ROS) [7] focuses on the selection of the best replica of a data file for a given job, taking into account the location of the computing resources and network and storage access latencies.

Network monitoring information provided by external EDG services is used by the ROS to obtain information on network latencies between the various Grid resources. This information is used to calculate the expected transfer time of a given file with a specific size. The ROS can also be used by the Resource Broker to schedule user jobs to the site from which the data files required can be accessed in the shortest time.

The ROS is implemented as a light-weight web service that gathers information from the European DataGrid network monitoring service and performs file access optimization calculations based on this information.

3.5. Service Interactions

The interaction between the various replica management services can be explained through a simple case of a user wishing to make a copy of a file currently available on the Grid to another Grid site (Figure 3.5). The user supplies the LFN of the file and the destination storage location to the Replica Manager (1). The Replica Manager contacts the RMC to obtain the GUID of the file (2), then uses this to query the RLS for the locations of all currently existing replicas (3). The ROS calculates the best site from which the file should be copied based on network monitoring information (4). The Replica Manager then copies the file (5) and registers the new replica information in the RLS (6).

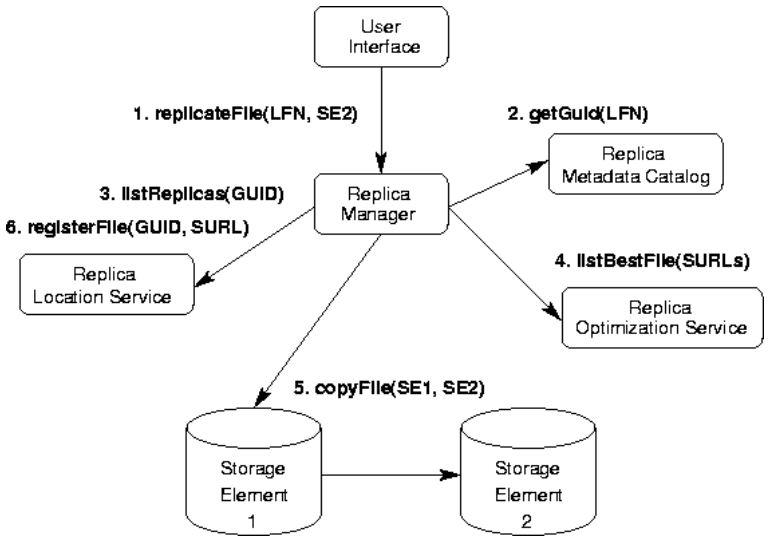

Figure 2. Typical usage of the EDG data mangement services.

4. Evaluation of Data Management Services

Grid middleware components must be designed to withstand heavy and unpredictable usage and their performance must scale well with the demands of the Grid. Therefore all the WP2 services were tested for performance and scaleability under stressful conditions. Some results of these tests are presented in this section and they show the services can handle the loads as expected and scale well.

Clients for the services are available in three forms: C++ API, Java API, and a Command Line Interface (CLI). It was envisaged that the CLI, typing a command by hand on the command line of a terminal, would be mainly used for testing an installation or individual command. The APIs on the other hand would be used directly by applications' code and would avoid the need for the user to interact directly with the middleware. Tests were carried out using all three clients for each component and as the results will show, using the API gives far better performance results than using the CLI. The reasons for this will be explained in this section.

All the services can be run as secure or insecure services. Security within the services is based on the Grid Security Infrastructure (GSI) [11] developed by Globus adapted for the web services architecture used by the WP2 replica management services. The use of secure services involves mutual authentication to establish the identities of both the client and server and authorization mechanisms to determine the access rights of the user for the particular service. This can add a significant overhead to the performance of the services involved. Here results are shown from tests using both secure and insecure services.

The performance tests were run on the WP2 testbed, consisting of 13 machines in 5 different sites. All the machines had similar specifications and operating systems and ran identical versions of the WP2 middleware. The application server used to deploy the services was Apache Tomcat 4 and for storing data on the server side, MySQL was used. For most of the performance tests small test applications were developed; these are packaged with the software and can therefore be re-run to check the results obtained.

4.1. Replica Location Service

Within the European DataGrid testbed, the RLS so far has only been used with a single LRC per Virtual Organization (group of users collaborating on the same experiment or project). Therefore results are presented showing the performance of a single LRC.

Firstly, the C++ client was tested using a test suite which inserts a number of GUID:SURL mappings, queries for one GUID and then deletes the mappings. This tests how each of these operations on the LRC scales with the number of entries in the catalog.

Figure 3(a) shows the total time to insert and delete up to 10 million mappings, and Figure 3(b) shows how the time to query one entry varies with the number of entries in the LRC. These tests were run without GSI security.

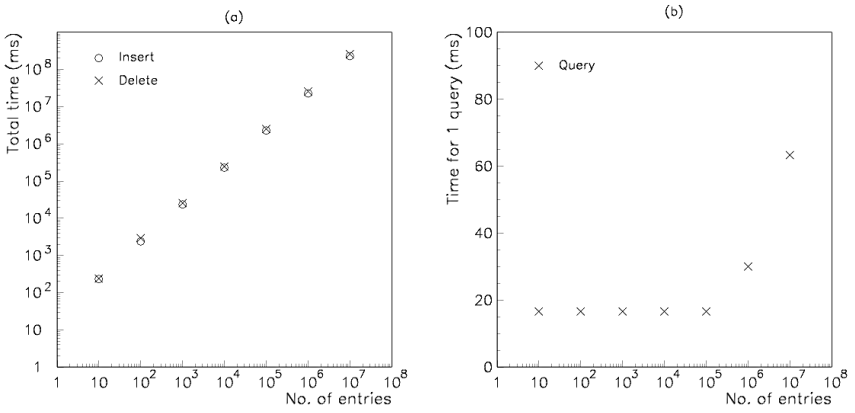

Figure 3. (a) Total time to add and delete mappings and (b) query the LRC using the C++ API.

The results show that insert and delete operations have stable behaviour, in that the total time to insert or delete mappings scales linearly with the number of mappings inserted or deleted. A single transaction with a single client thread takes about 25 - 29 ms with the tendency that delete operations are slightly slower than inserts. The query time is independent of the number of entries in the catalog up to around 1 million entries, when it tends to increase.

Taking advantage of the multiple threading capabilities of Java, it was possible to simulate many concurrent users of the catalog and monitor the performance of the Java API.

The first test was done with 10 concurrent threads, where at any given moment 5 threads would be inserting a mapping and 5 threads would be querying a mapping. Figure 4 compares insert time and query time for the LRC with varying numbers of entries using (a) a secure service and (b) an insecure service. Using security creates significant overheads due to the creation of a secure communications channel between the client and server and the time to authorise client requests according to a certain access control policy. In this case these extra

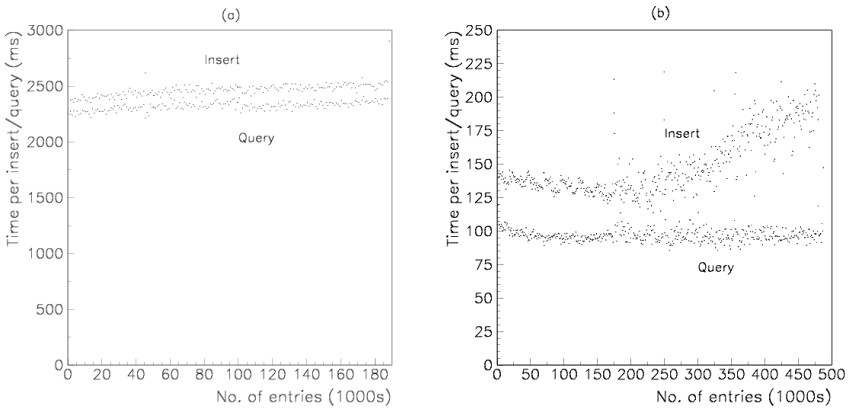

Figure 4. Time to insert mappings and query one GUID for different numbers of entries in the LRC, using 5 concurrent inserting clients and 5 concurrent querying clients with (a) a secure service and (b) an insecure service.

processes make catalog operations take up to 20 times longer than operations on an insecure catalog.

In Figure 4(a) the variation of operation times with the number of entries is somewhat obscured by the large security overhead but in general queries take slightly less time than inserts. The trend is a lot clearer in Figure 4(b), which shows the insert time rising from 140 ms to 200 ms as the catalog fills up but the query time remaining at a constant 100 ms and not varying with the number of entries.

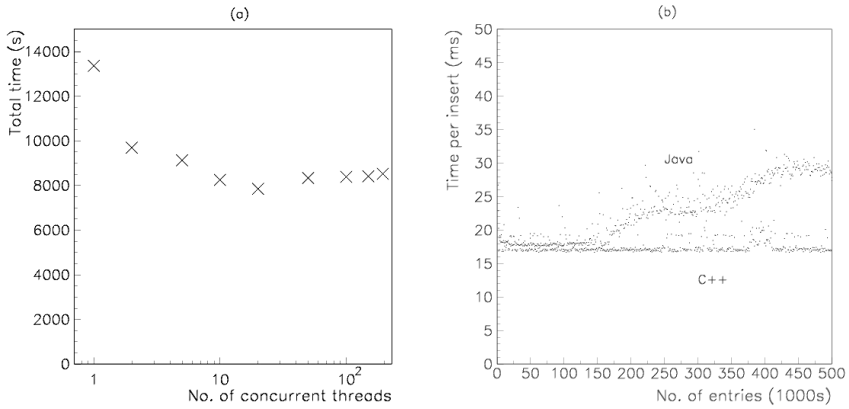

Figure 5. (a) Total time to add 500,000 mappings to the LRC using concurrent threads and (b) comparison of Java and C++ API performance.

To measure the effective throughput of the LRC, i.e. the time to complete the insert of a certain number of entries, the total time to insert 500,000 mappings was measured for different numbers of concurrent threads using the Java API on an insecure service. Figure 5(a) shows that the time falls rapidly with increasing numbers of threads, bottoming out after 10 or 20 threads. For 20 threads the total time taken is about 40% less than using one thread. Although the time for an individual operation is slower the more concurrent operations are taking place, the overall throughput actually increases, showing the ability of the LRC to handle multiply threaded operations.

A direct comparison between the Java and C++ API performance when inserting one mapping into the LRC for varying numbers of entries in the catalog is given in Figure 5(b). This test was carried out with one client thread operating on an insecure service and the results confirm the behaviour seen in Figure 3(a) and Figure 4(b), that C++ has much more stable and performant behaviour than Java. The total time to complete the 500,000 operations was just over 9000s using the C++ API and almost 13500s with the Java API, a difference of 50%.

Similar performance tests on the C-based Globus implementation of the Replica Location Service framework are presented in [14]. Here peak performance is also seen when around 10 concurrent client threads are using the service, however the rates of operations achieved are much higher, reaching 750 inserts and 2000 queries per second (after tuning certain database backend parameters).

4.2. Replica Metadata Catalog

The Replica Metadata Catalog can be regarded as an add-on to the RLS system and is used by the Replica Manager to provide a complete view on LFN:GUID:SURL (Figure 1) mapping. In fact the way the RMC and LRC are used is exactly the same, only the data stored is different and thus one would expect similar performance from both components.

In the European DataGrid model, there can be many user defined LFNs to a single GUID and so the behaviour of the RMC was analysed in the case where there were multiple LFNs mapped to a single GUID. Figure 6(a) shows the time to insert and delete 10 GUIDs with different numbers of LFNs mapped to each GUID and Figure 6(b) shows the time to query for 1 LFN with varying numbers of LFNs per GUID. These tests used the C++ API and an insecure service.

The insert/delete times increase linearly as one might expect, since each new LFN mapping to the GUID is treated in a similar way to inserting a new mapping, thus the effect is to give similar results to

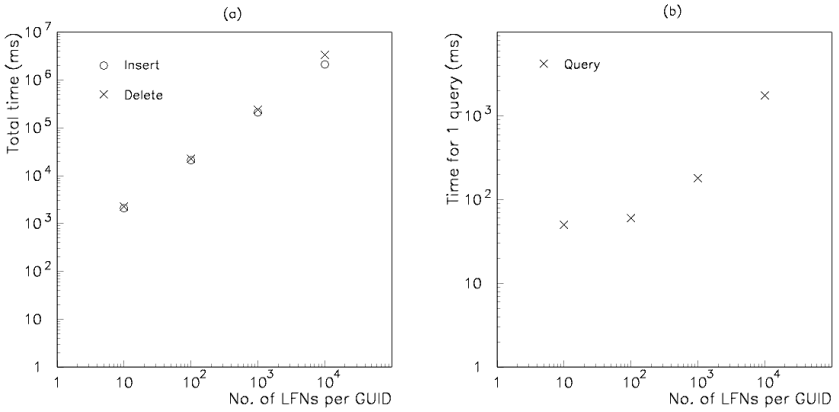

Figure 6. Total time to (a) insert and delete 10 GUIDs with varying number of LFNs, and (b) query for one LFN.

the insert times for the LRC seen in Figure 3 in terms of number of operations performed. Query operations take longer the more LFNs exist for a single GUID, however the query time per LFN mapped to the GUID actually decreases the more mappings there are, hence the RMC performance scales well with the number of mappings associated with each GUID.

Along with LFN aliases, in the RMC users can define O(10) associated metadata attributes to each alias, such as date created, file size or application specific data such as the energy used to create a specific physics event or the coordinates of a satellite image. This data can be used to query a subset of data from the catalog.

The time to insert mappings into the catalog including these attributes was measured and results are shown in Figure 4.2. Mappings were inserted with 1, 5 or 10 attributes where half the attributes were string attributes and half were integer attributes. In all cases one thread performed the inserts using the Java API and an insecure RMC service.

It can be seen that adding an attribute to an alias takes an equivalent amount of time to adding the mapping itself, i.e. 25-30 ms. The number of attributes added and hence the increasing amount of information held by the database does not affect the insert timings, as the three sets of results have essentially the same shape, in that there is a very gradual increase in insert time as the number of entries in the catalog increases.

The command line interface for all the services is implemented in Java using the Java API. Table I shows some timing statistics giving

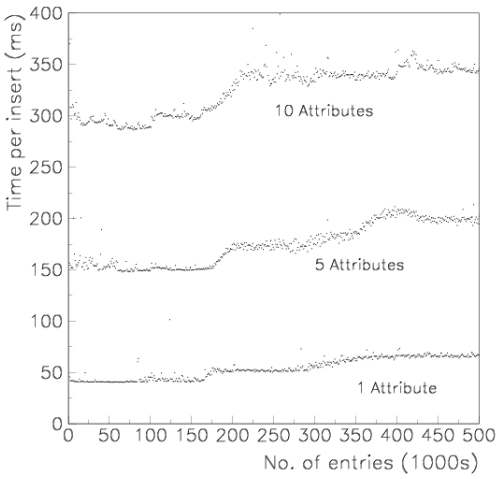

Figure 7. Variation of insert time with different numbers of entries in the catalog and different numbers of attributes per entry.

the time to execute different parts of the command addAlias used to insert a GUID:LFN mapping into the RMC using a secure service.

Table I. Timing statistics for adding a GUID:LFN mapping in the RMC using the CLI.

Time (s)	Operation
0 - 1.0	Start-up script and JVM start-up time
1.0 - 1.1	Parse command and options
1.1 - 2.1	Get RMC service locator
2.1 - 2.3	Get RMC object
2.3 - 3.7	Call to the rmc.addAlias() method
2.3 - 3.0	Java class loading
3.0 - 3.6	Security authorisation
3.6 - 3.7	Database operations
3.7	End

The total time to execute the command was 3.7s and this time is broken down into the following areas: The start-up script sets various options such as logging parameters and the class-path for the Java

executable and this, along with the time to start the Java Virtual Machine, took 1.0s. After parsing the command line it took a further 1.0s to get the LRC service locator - during this time many external classes had to be loaded in.

The call to the addAlias() method within the Java API took around 1.4s, mainly due to the Java dynamic class loading that takes place first time a method is called (0.7s) and the security authorisation (0.6s). The database operations themselves took less than 0.1s. Compared to the average over many calls of around 25 ms observed above in the API tests, this is very large, and because every time the CLI is used a new JVM is started up, the time to execute the command is the same every time.

In short, the time taken to insert a GUID:LFN mapping into the RMC using the command line interface is about 2 orders of magnitude longer than the average time taken using the Java or C++ API. Therefore the command line tool is only recommended for simple testing and not for large scale operations on the catalog.

5. Open Issues and Future Work

Most of the services provided by WP2 have satisfied the basic user requirements and the software system can be used efficiently in a Data Grid environment. However, several areas still need work.

5.1. User Feedback

There are a number of capabilities that have been requested by the users of our services or that we have described and planned in the overall architecture but did not implement within the project.

There is currently no proper *transaction support* in the Replica Management services. This means that if a seemingly atomic operation is composite, like copying a file and registering it in a catalog, there is no transactional safety mechanism if only half of the operation is successful. This may leave the content of the catalogs inconsistent with respect to the actual files in storage. A *consistency service* scanning the catalog content and checking its validity also would add to the quality of service.

The other extreme is the grouping of several operations into a single transaction. Use cases from the high energy physics community have shown that the granularity of interaction is not on a single file or even of a collection of files. Instead, they would like to see several operations managed as a single operative entity. These are operations on sets of

files, spawned across several jobs, involving operations like replication, registration, unregistration, deletion, etc. This can be managed in a straightforward manner if replica management jobs are assigned to a session. The *Session Manager* would hand out session IDs and finalize sessions when they are closed, i.e. only at that time would all changes to the catalogs be visible to all other sessions. In this context sessions are not to be misinterpreted as transactions, as transactions may not span different client processes; sessions are also managed in a much more lazy fashion.

We have also received requests for the support of *file-system semantics* in the logical file namespace, including the support for directories and *fine-grained access control* mechanisms in the catalog layer. The directory support in the logical namespace would satisfy most requests for proper *file collections* if metadata can also be associated with directory entries. For more complex collection semantics there might be the need for additional metadata.

In the original WP2 design, *pre- and post-processing hooks* were foreseen to be available through the Replica Manager. The reason to have such hooks is that many Virtual Organizations have use-cases concerning replication where they have to add some processing before the data can be replicated. These can be checksums, specialized validation after copy, encryption and decryption of data, additional entries to be made in application catalogs, actual data generation from templates, etc.

5.2. Future Services

There are several other services that need to be addressed in future work. In the first prototype of the European DataGrid testbed WP2 provided a *replica subscription facility*, GDMP [25]. The hope was to replace GDMP with a more robust and versatile facility fully integrated with the rest of the replication system, but this was not done due time pressures. The functionality to automatically distribute files based on some subscription mechanism is still much-needed.

In terms of *Metadata Management*, currently the metadata support in the RMC is limited to of O(10) basic typed attributes, which can be used to select sets of LFNs. The RMC cannot support many more metadata attributes or more complex metadata structures. There is ongoing work in the context of the GGF DAIS working group to define proper interfaces for data access and integration, much of their findings can be used to refine and re-define the metadata structures of the RMC.

5.3. Future Optimisation Strategies

The current ROS component is conservative in terms of functionality, and there has been much recent research in this area [12, 21, 23] that should be leveraged to improve the capabilities and performance of the optimisation systems. This would include the facility for the service to automatically replicate popular data sets based on previous access history, or pre-stage files based on job requirements before a job starts running.

5.4. Adhering to Standards

The Open Grid Service Architecture (OGSA) [18] is a GGF effort to describe Grid service architectures which define in generic terms the structure and mechanisms that have to be made available by Grid services in order to be "OGSA compliant". The current versions of these Grid standards are extensions of the standard web service frameworks already used for WP2 software, consequently the migraton to any of these newly emerging Grid standards should be straightforward.

6. Related Work

As mentioned, one of the first Grid replica management prototypes was GDMP [25]. In its first toolkit the Globus project [1] provided an LDAP-based replica catalog service and a simple replica manager that could manage file copy and registration as a single step. The initial implementation of the EDG Replica Manager simply wrapped these tools, providing a more user-friendly API and mass storage bindings. Later, we developed the concept of the Replica Location Service (RLS) together with Globus [13]. Both projects have their own implementation of the RLS and the performance of the Globus implementation is examined in [14].

In terms of storage management, we have participated actively in the definition of the Storage Resource Management (SRM) [8] interface specification. Work is being carried out on a Reliable File Transfer service [3] by the Globus Alliance, which may be exploited by future high-level data management services for reliable data movement. An integrated approach for data and meta-data management is provided in the Storage Resource Broker (SRB) [6].

Within the high energy physics community one of the most closely related projects is SAM [26] (Sequential data Access via Metadata) that was initially designed to handle data management issues of the D0 experiment at Fermilab. Another data management system as part

of the Condor project is Kangaroo [27], which provides a reliable data movement service. It also makes use of all available replicas in its system such that this is transparent to the application.

Related work with respect to replica access optimization has been done in the Earth Science Grid (ESG) [2] project, which makes use of the Network Weather Service (NWS) [33]. Optimized replica selection based on ClassAd match-making between storage resources and application requirements, whereby the storage resources can be ranked by attributes such as available space or maximum data transfer rate is discussed in [30]. Further studies in the field of optimized data replication have been presented in [12] and [23].

Various solutions have been proposed to data management in peer-to-peer environments, however these tend to concentrate on a specific requirement of a certain group of users. Gnutella [19] provides a rapid querying system at the expense of flooding the network with messages while Freenet [15] uses a more conservative querying system to pin-point data location and guarantees anonymity for all users. Free Haven [16] also provides anonymous read and write access on the network and concentrates on guarenteeing persistency of data. These systems work well for millions of users sharing small files but are not robust or reliable enough for the specialised requirements of smaller groups of scientists.

Some companies are now starting to offer replication-based solutions to the data handling needs of industry. Avaki for example focusses on simplifying access to data from multiple heterogeneous sources. A data servce layer lies between any number of data sources and any number of data applications and for the applications it appears as one virtual data source.

7. Conclusion

In this paper we have described the design and architecture and examined the performance of the data management services provided to the European DataGrid project by Work Package 2. The web services model was used to create a set of independent replication, cataloging and optimization services accessed via a single entry point, the Replica Manager. The adoption of the web services model enables a platform and vendor independent means of accessing and managing the data and associated metadata of the user applications. Performance analysis has shown that when the services are used as intended, they can cope under stressful conditions and scale well with increasing user load.

It remains to be seen what the final standard will be for a Grid services framework. But the data management services we have developed should be adaptable with minimal effort to the emergent standards and can provide a solid base for any future efforts in this area.

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