

# Monitoring and Migration of a PETSc-based Parallel Application for Medical Imaging in a Grid computing PSE\*

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## 1 Introduction

In last decades, imaging techniques became central to the diagnostic process providing the medical community with a fast growing amounts of information held in images. This implies developing computational tools which allow a reliable, robust and efficient processing of data and enhanced analysis. Moreover, clinicians may have the need to explore collaborative approaches and to exchange diagnostic information from available data. A medical experiment often involves not a single approach but a set of processings that should be sometimes executed concurrently.

Grid computing is becoming a cost effective emerging technology for high performance computing aggregating resources that cannot be available locally [16]. In particular, grid technologies are a promising tool to deal with current challenges in medical domains. On the other hand, employing a distributed infrastructure, where nodes may be geographically scattered all around the world and not dedicated to a specific application, is not without a price. The challenge of the grid computing paradigm derives mainly from the dynamic nature of resource requirements. In this context, in particular, reliability is a key issue and critical to the correct diagnosis.

Here we are concerned with improvements and enhancements of a medical imaging grid enabled infrastructure, named MedIGrid, oriented to the transparent use of resource-intensive applications for the management, processing and visualization of biomedical images [5, 8, 6]. MedIGrid has been designed so that users can schedule reconstruction jobs needed in tomographic nuclear imaging or the denoising of ultrasound images arising in 3D echocardiography.

In this paper we focus on the optimization of the software routines of MedIGrid for dynamically adapting to changes in the computational nodes. More

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precisely, we deal with the monitoring and the migration of a parallel algorithm based on the PETSc library [3] for denoising of 3D ultrasound images.

The paper is organized as follows: in Sec. 2 a brief description of MedIGrid infrastructure is presented, in Sec. 3 the images reconstruction application is introduced, in Sec. 4 the Performance Contract System and its implementation inside the PETSc parallel algorithm is discussed, finally in Sec. 5 conclusions and future work are presented.

## 2 MedIGrid infrastructure

The testbed we are presently using, is made of acquisition systems and storage resources located in Florence (Careggi Hospital) and Genoa (S. Martino Hospital), computational resources in Naples and Lecce, grid access points in Naples and Genoa. The client side allows to set up the input and to monitor the reconstruction process by means of a user-friendly graphical interface. More precisely, the computational servers are:

IA-64-1 : cluster of 60 nodes operated by the INFN (Istituto Nazionale Fisica Nucleare). Each node of the cluster is composed by two Itanium 2 processors running at 1.4 GHz and with 4 GB of main memory. The nodes are connected by a switch Quadrics QSNNet II. The operating system is Red Hat Enterprise 3 Linux, equipped with the hp-mpi, PETSc 2.2.1 and Autopilot;

IA-64-2 : cluster located at the University of Lecce with the same features of IA-64-1;

UniPart1 : cluster of 8 nodes located at the University of Naples, Parthenope. Each node is an Intel Pentium 4 HT running at 3 GHz with a main memory of 512 MB. The operating system is Fedora Core 3 Linux, equipped with mpich 1.2.7, PETSc 2.2.1 and Autopilot;

UniPart2 : cluster of 25 nodes operated by the University of Naples, Parthenope. Each node is an Intel Pentium 4 HT running at 2.8 GHz with a main memory of 512 MB. The operating system is Fedora Core 3 Linux, equipped with mpich 1.2.6, PETSc 2.2.1 and Autopilot.

The clusters in Naples are connected by a 1 Gbits metropolitan area network, while Naples and Lecce are linked by a 155 Mbits wide area network; the Globus 4 middleware has been used to build the computational grid.

More recently, the system has been upgraded with several new, advanced features, including grid services, available through the User Portal; an application oriented brokering service, as part of the application manager, to enable dynamic discovery and allocation of computing resources, an xml based configuration model to set parameters related to the execution of the software [7].

The following section describes the parallel algorithm that we have developed, using PETSc, for denoising a sequence of 3D ultrasound images of the heart [9].

### 3 The PETSc-based parallel algorithm

A 3-D image is the function

$$u_0(x_1, x_2, x_3) : \Omega \longrightarrow \mathfrak{R}_0^+, \quad \Omega \subset \mathfrak{R}^3; \quad (1)$$

a 3-D sequence of images is the function:

$$u_0(x_1, x_2, x_3, \theta) : \Omega \times I \longrightarrow \mathfrak{R}_0^+, \quad \Omega \subset \mathfrak{R}^3, \quad (2)$$

where  $I := [0, T]$  is the time interval during which the acquisition of the sequence has been performed. We consider the following equation describing the denoising of the 3-D sequence:

$$\frac{\partial u}{\partial t} = clt(u) \nabla \cdot (g(|\nabla u_\sigma|) \nabla u); \quad (3)$$

[11, 22]. Equations are accompanied with zero-Neumann boundary conditions in space, initial condition is given by (2); finally, we suppose periodic boundary conditions in time.

The function  $clt(u)$  is a scalar function representing a measure of coherence in time for the moving structures [21];  $g = g(s)$  is a continuous function satisfying:

$$g(0) = 1, \quad \lim_{s \rightarrow \infty} g(s) = 0, \quad (4)$$

and  $u_\sigma := G_\sigma * u$  is obtained convolving  $u$  with a 3-dimensional Gauss function of zero mean and variance equal to  $\sigma$ ,

$$G_\sigma = \frac{1}{(2\sqrt{\pi\sigma})^3} e^{-|x|^2/4\sigma}. \quad (5)$$

In order to compute  $u_\sigma$  we have to solve the Heat equation:

$$\frac{\partial u}{\partial t} = \nabla \cdot (\nabla u) \quad (6)$$

in  $[0, \sigma]$  with initial condition  $u_0$ . We now briefly describe a common numerical scheme for the discretization of (3). Details can be found in [9].

Let  $N = n_1 \times n_2 \times n_3$  be the dimension of the 3-D frame,  $n_{scales}$  the number of scale steps that are performed and, finally,  $\tau$  be the discrete scale step; let us consider a space-time sequence consisting of  $n_4$  3-D frames of dimension  $N$ , and let  $\theta := T/(n_4 - 1)$  be the discrete time step; we denote by  $u_j^i$  the  $j$ th frame in the  $i$ th scale step,

$$u_j^i(x_1, x_2, x_3) := u(i\tau, x_1, x_2, x_3, j\theta), \quad (7)$$

where

$$\begin{aligned} i &= 0, 1, \dots, n_{scales} - 1, \\ x_1 &= 0, 1, \dots, n_1 - 1, \\ x_2 &= 0, 1, \dots, n_2 - 1, \\ x_3 &= 0, 1, \dots, n_3 - 1, \\ j &= 0, 1, \dots, n_4 - 1. \end{aligned}$$

Numerical discretization has been performed by using a semi-implicit scheme in scale, that is the nonlinearities are treated using the previous scale step, then linearized, while the linear terms are handled implicitly. Semi-implicit discretizations of  $u_j^i(x_1, x_2, x_3)$  is shown in Fig. 1.

```

u(x, 0) = u_0
% loop over the scales
for i = 1, n_scales do
  % loop over the frames
  for j = 0, m do
    solve  $\frac{u_j^i - u_j^{i-1}}{\tau} =$ 
           $clt(u_j^{i-1}) \nabla \cdot (g(|\nabla(u_j^{i-1})_\sigma|) \nabla u_j^i)$ 
  endfor
endfor

```

**Fig. 1.** semi-implicit scheme for the numerical solution of (3).

The semi-linear discrete equations that arise, i.e. :

$$\frac{u_j^i - u_j^{i-1}}{\tau} = clt(u_j^{i-1}) \nabla \cdot (g(|\nabla(u_j^\sigma)|) \nabla u_j^i), \quad (8)$$

are discretized in space via finite volume method [18]; we solve (6) with a semi-implicit scheme in scale as well, that is:

$$\frac{u_j^\sigma - u_j^{i-1}}{\sigma} = \nabla \cdot (\nabla u_j^\sigma), \quad (9)$$

where finite volume discretization in space has been used as for the equation (8).

Two main computational kernels arise, that is, the solution at each scale step  $i$  and for each frame  $j$ , of the linear systems:

$$\mathbf{A}_{HE} \mathbf{u}_j^\sigma = \mathbf{b}_j^i, \quad (10)$$

$$\mathbf{A}_{ME} \mathbf{u}_j^i = \mathbf{b}_j^i, \quad (11)$$

with

$$\mathbf{A}_{HE}, \mathbf{A}_{ME} \in \mathbb{R}^{N \times N}, \mathbf{b}_j^i \in \mathbb{R}^N,$$

where (10) refers to the space discretization of (9) and (11) to that of (8).

In Fig. 2. a schematic description of the algorithms that we have implemented is shown. The matrix  $\mathbf{A}_{HE}$  depends upon  $\sigma$  and the size of the space discretization grid, so it is built only once, while  $\mathbf{A}_{ME}$  depends upon quantities that change their value both with the scale step and the frame. As a consequence, its entries have to be recomputed  $m \times n_{scales}$  times. Right-hand side  $\mathbf{b}_j^i$  contains the values of  $\mathbf{u}_j^{i-1}$ , i.e. the frame at the previous scale.

```

build  $\mathbf{A}_{HE}$ 
% loop over the scales
for  $i = 1, n_{scales}$  do
  % loop over the frames
  for  $j = 0, m$  do
    1. Init  $\mathbf{A}_{HE} \mathbf{u}_j^\sigma = \mathbf{b}_j^i$ 
    2. solve  $\mathbf{A}_{HE} \mathbf{u}_j^\sigma = \mathbf{b}_j^i$ 
    3. build  $\mathbf{A}_{ME}$ 
    4. solve  $\mathbf{A}_{ME} \mathbf{u}_j^i = \mathbf{b}_j^i$ 
  endfor
endfor

```

**Fig. 2.** multiscale analysis of a sequence of 3-D frames: outline of the algorithm.

Both  $\mathbf{A}_{HE}$  and  $\mathbf{A}_{ME}$  are large, sparse and structured; more precisely, their non-zero elements are located along seven diagonals: the principal diagonal and the three upper and lower diagonals respectively. Since we use the same discretization scheme both for (9) and (8),  $\mathbf{A}_{HE}$  and  $\mathbf{A}_{ME}$  have the same symmetric sparsity pattern; finally,  $\mathbf{A}_{HE}$  is symmetric with respect to its entries as well, while  $\mathbf{A}_{ME}$  is not for the presence of function  $clt(u)$  in equation (3).  $\mathbf{A}_{HE}$  and  $\mathbf{A}_{ME}$  are positive definite  $M$ -matrices symmetric in their structure.  $\mathbf{A}_{HE}$  is besides symmetric with respect to its entries too. The properties we mentioned motivate the effectiveness of two popular Krylov projection methods, the Conjugate Gradient (CG) and the General Minimal Residual (GMRES) [13]. Both CG and GMRES are provided by the PETSc library [3]. Parallel approach is domain decomposition-based, i.e., we distribute the image domain among processes. In particular, we choose the **Slice Partitioning**, that is, the image is partitioned along one single dimension. Let  $\Omega \subset \mathbb{R}^3$  be the image domain, as defined in (1) and (2);  $\Omega$  is a rectangular domain, with  $n_1, n_2, n_3$  be its three dimensions. We distribute the domain along the third dimension only: if  $p$  is the number of processes, each process  $id$ ,  $0 \leq id \leq p - 1$ , will have

$n_{id}$  slices of the 3-D image (that is,  $n_1 \times n_2 \times n_{id}$  voxels), where:

$$n_{id} = \begin{cases} n_3/p + 1 & id < (n_3/p) \\ n_3/p & otherwise. \end{cases} \quad (12)$$

Let  $(i, j, k)$  be the coordinates of a voxel  $V_l$  in the  $n_1 \times n_2 \times n_3$  image; voxels are numbered in a row-major fashion on successive planes, so, since each voxel generates one equation of the linear system and  $l$  corresponds exactly to the number of the equation generated by  $V_l$ , it follows that the slice partitioning gives rise to a *row-block fashion* distribution of the system matrix, that is, blocks of contiguous rows are distributed among contiguous processes. Slice partitioning has been chosen because the row-block fashion distribution is the standard PETSc matrices decomposition, and redistribution before the solution of the linear systems, is avoided.

## 4 Monitoring and Migration of the algorithm

The software architecture of MedIGrid is composed of three main layers: *core services*, based on the Globus toolkit, *collective services*, including the Resource Broker (RB) and the Performance Contract System (PCS), and the *Application Manager* (AM) that collects the software units that deeply interact with the algorithms during their execution. Some previous works refer to the Performance Contract System and to the Resource Broker [10, 17]. Here we focus on the deployment of the PCS for steering the performance of the parallel algorithm as described in section 3 in Figure 2. To this aim, following [2, 4] the reference workflow of the AM can be sketched as follows: the AM invokes the Performance Modeler with input parameters and information related to the computational resource. The Performance Modeler provides an execution model of the algorithm. The execution model, the input parameters and the machine parameters are given as "contract" to a Contract Developer. If the contract is approved the AM provides to spawn the job on the given resource. The Contract Monitor, monitors the times taken by the application while the AM waits for the job to complete. The job can either complete or, in case of contract violation, suspend its execution. If the job has completed the AM exits. If the job is suspended, the AM collects new information given by the brokering service and by the Contract Developer and it starts the phase again. In this latter phase a migration of the application onto another available resource can occur in such a way that the performance contract is satisfied. Hence, the entire process consists of a Periodical rescue of the execution state (**recovery**); a Run-time check of the execution flow (**monitoring**); a Process resumption on alternative resource (**migration**).

The contract verification consists of comparing the execution time of the algorithm with the one stated in the Performance Contract itself. We consider, as expected performance, the execution time of a computational kernel of the

algorithm. In particular, we consider the execution time needed for denoising frame 1 at scale 1.

To monitor the algorithm, the *Autopilot* library [20] is used. The algorithm is instrumented by means of *sensors* and *actuators* to enable it to adapt its flow according to the performance level.

The migration step is aimed to suspend and migrate the execution of the algorithm on another resource in such a way that the performance contract is satisfied. We enable the parallel algorithm for saving current state and for restarting on another resource. More precisely, as shown in Figure 2, the algorithm consists essentially of two nested loops: the outermost over scale  $i$  and the innermost over the frame  $j$ . Denoising a single frame at each scale is performed by four steps: the first (*init*) and the third (*build*) steps have a computational complexity that does not depend on  $i$  and  $j$ , whereas the computational cost of the second (the parallel CG) and the fourth (the parallel GMRES) depend on the number of iterations needed to reach the requested tolerance, hence it depends on  $i$  and  $j$ . Note that both CG's steps and GMRES's steps have a computational cost that depends only on the size of the frame.

In order to select a resource on the basis of its computational power it is a common way to run a benchmark by the Performance Modeler [1, 14]. As benchmark of the  $k$ -th computational nodes of the grid, we consider the execution time,  $T^{(0)}(1, 1)$ , needed for denoising frame 1 at scale 1:

$$T^{(k)}(1, 1) = T_{init}^{(k)} + T_{CG}^{(k)}(1, 1) + T_{build}^{(k)} + T_{GMRES}^{(k)}(1, 1) \tag{13}$$

where:

- $T_{init}^{(k)}$  is the execution time of step 1
- $T_{CG}^{(k)}(1, 1)$  is the execution time of step 2 on frame 1 at scale 1
- $T_{build}^{(k)}$  is the execution time of step 3
- $T_{GMRES}^{(k)}(1, 1)$  is the execution time of step 4 on frame 1 at scale 1

Starting from the benchmark on the first frame we can provide an estimate of the execution time of the algorithm on a generic frame. Let:

- $\Delta_{CG}(i, j)$  be the number of iterations of step 2 on the frame  $j$  at scale  $i$
- $\Delta_{GMRES}(i, j)$  be the number of iterations of step 4 on the frame  $i$  at scale  $j$

then

$$\frac{\Delta_{CG}(i, j)}{\Delta_{CG}(1, 1)} T_{CG}^{(k)}(1, 1) \quad \text{and} \quad \frac{\Delta_{GMRES}(i, j)}{\Delta_{GMRES}(1, 1)} T_{GMRES}^{(k)}(1, 1)$$

provide respectively an estimate of the execution time of *CG* and of *GMRES* on frame  $i$  at scale  $j$ .

Using the benchmark given by (13), taking into account that both  $T_{init}^{(k)}$  and  $T_{build}^{(k)}$  do not depend on  $i$  and  $j$ , the expected execution time needed for denoising frame  $j$  at scale  $i$  on the  $k$ -th node, and used by the Performance Contract, is the following:

$$PC^{(k)}(i, j) = T_{init}^{(k)} + \frac{\Delta_{CG}(i, j)}{\Delta_{CG}(1, 1)} T_{CG}^{(k)}(1, 1) + T_{build}^{(k)} + \frac{\Delta_{GMRES}(i, j)}{\Delta_{GMRES}(1, 1)} T_{GMRES}^{(k)}(1, 1) \quad (14)$$

A first set of experiments has been executed with the aim of validating (14). These experiments are executed on clusters **IA-64-1** and **UniPart1**. Tables 1 and 2 report results concerning the denoising of a sequence of 14 frames of size  $151 \times 151 \times 101$ . We show the Performance Contract  $PC^{(0)}(1, j)$  related to node 0 for all values of  $j$  (the frames) and for  $i = 1$  (one scale), and the execution time  $T^{(0)}(1, j)$  (in seconds) for denoising the frame  $j$ . Further we show, in the last column, the relative error obtained estimating the actual execution time and that estimated by the Performance Contract. Note that the error is of 10% at most. Results refer only to node 0 because we did not observe significant differences with the other nodes of the clusters **IA-64-1** and **UniPart1**.

**Table 1.** Monitoring on the cluster IA-64-1

Frame index	$PC^{(0)}(1, j)$ (in secs.)	$T^{(0)}(1, j)$ (in secs.)	Relative error
1	20.9512	20.9512	0.00
2	14.4678	13.3022	0.08
3	14.7625	13.5491	0.08
4	15.6466	14.4584	0.08
5	16.5307	15.3111	0.07
6	16.2360	15.0253	0.07
7	15.6466	14.3392	0.08
8	14.7625	13.5789	0.08
9	14.4678	13.2639	0.08
10	15.6466	14.3577	0.08
11	15.3519	14.0668	0.08
12	15.6466	14.3602	0.08
13	15.6466	14.2467	0.09
14	19.7724	18.8719	0.05

Migration is a crucial task, because it depends on the relative overhead. Of course, such overhead may drastically change if migration occurs on nodes of the same resource or it is needed to migrate on another resource. In the Table 3 we report, in the first column the time (in seconds) needed to migrate on other nodes of the same cluster (we refer to the *local* migration), in the second column we report the time (in seconds) needed to migrate on different resources of the same geographic area, and we consider the two clusters located in Naples. Finally, in the third column, we report the time (in seconds) needed to migrate on the cluster located in Lecce (we refer to these last two cases as to a *remote* migration).

**Table 2.** Monitoring on the cluster UniPart1

Frame index	$PC^{(0)}(1, j)$ (in secs.)	$T^{(0)}(1, j)$ (in secs.)	Relative error
1	28.0687	28.0687	0.00
2	21.9950	20.3260	0.08
3	22.2711	20.6368	0.07
4	23.0993	20.9746	0.09
5	23.9275	21.5562	0.10
6	23.6515	21.2710	0.10
7	23.0993	20.8936	0.10
8	22.2711	20.1092	0.10
9	21.9950	19.9545	0.09
10	23.0993	20.8051	0.10
11	22.8232	20.7351	0.09
12	23.0993	20.7394	0.10
13	23.0993	20.8089	0.10
14	26.9644	25.4509	0.06

**Table 3.** Local vs. Remote Migration time (secs.)

Task	Local Naples area wide area		
New resources selection	0	240	240
Data moving (1 frame=3MB)	0	6	0.2
Application starting	1	1	1

As expected, the overhead introduced by the resource brokering in case of remote migration, is much larger than that for the local migration. Therefore, let:

- $T_{mo}$  be the migration overhead, as reported in Table 3;
- $R_{old}$  be the execution time needed to terminate the algorithm on the initial resource;
- $R_{new}$  be the execution time needed to terminate the algorithm on the resource where it migrates;

then, a migration on another resource occurs if

$$R_{new} + T_{mo} < R_{old}$$

where  $R_{old}$  is estimated by the Migration Manager as follows:

$$R_{old} = \hat{T} \cdot nscales \cdot RF$$

where  $\hat{T}$  is the average time needed on for denoising the frames before the migration, and  $RF$  is the number of frames not yet denoised. To estimate  $R_{new}$  the Migration Manager evaluates the ratio between the benchmarks on the

two systems, as defined in (13). More precisely, let  $B_{old}$  and  $B_{new}$  respectively denote the average benchmarks computed on all nodes of the initial resource and of the alternative resource, then, the Migration Manager computes:

$$B_{new/old} = \frac{B_{new}}{B_{old}}$$

and we assume that:

$$R_{new} \simeq B_{new/old} R_{old}$$

From Tables 1, 2 and 3, we observe that a remote migration should occur only if a strong violation of the Performance Contract occurs while the algorithm is processing the first two or three frames. Otherwise, once first frames have been processed, the overhead makes the remote migration not convenient. However, in our experiments, the overhead relative to the remote migration is mainly due to the execution of the benchmark needed for the selection of an alternative resource. This step is executed at runtime when the Monitor detects a contract violation. Of course, to reduce this overhead, the benchmark values should have been already available.

## 5 Future Works

We are currently working on the introduction of a fault-tolerance mechanism into the PETSc based application combined with some kind of checkpointing [12, 19]. We are using an *algorithm-based* approach relying on FT-MPI [15] which provides the software tools needed to identify and manage faults. We are using a disk based checkpointing method, indeed the algorithm already writes onto the disk the vectors  $u_j^i$  for each  $i$  and  $j$ . Moreover, to compute the vector  $u_j^i$  we only need  $u_{j-1}^{i-1}$ ,  $u_j^{i-1}$  and  $u_{j+1}^{i-1}$ . Then, in order to recover from a fault we restart from those  $i$  and  $j$  corresponding to the last computed  $u_j^i$ , and the check of faults is performed at the end of each step of the innermost loop of the algorithm.

FT-MPI allows to re-spawn failed processes and to decide if to drop, or not, all ongoing messages. Moreover, when FT-MPI is used, the MPI context is redefined after each process is re-spawned. The main drawback seems to be the heavy dependence of all the PETSc global objects on the MPI context: i.e. the `PETSC_COMM_WORLD` macro, used by all PETSc objects, is a “copy” of the underlying `MPI_COMM_WORLD` MPI context. This suggests to address the fault-tolerance by the following steps:

- check the status of the processes: if a process has been re-spawned, then:
  - destroy the PETSc environment with all its objects,
  - re-initialize the PETSc environment and create all the PETSc objects that are needed,
- restart the iterations from the last computed and saved  $u_j^i$ .

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## **Q&A – Vania Boccia**

### **Questioner: David Keyes**

*PETSc, Aztec, Scalapack and other scientific libraries that you propose to be modified for fault-tolerance are in use worldwide and there is a potentially enormous interest in such a development. I recommend that any such modifications, to be accepted, be undertaken in conjunction with the developers. Please comment.*

### **Comment: Bill Gropp**

*The PETSc group is interested in understanding the best ways to integrate the changes or extensions you need to PETSc.*

#### **Vania Boccia**

The introduction of fault tolerance mechanisms as those described in the talk, on our PSE's numerical kernels requires the modification of the algorithms source code. In the case of MEDITOMO library in fact, we worked on its two algorithms (Conjugate Gradient and Expectation Maximization) to enable them to do fault management, by modifying their source codes. This is the reason because we didn't introduce these mechanisms on the second PSE library (ECOCCG). It is based on the PETSc library and we thought that every eventual modification in a such used library, should be done together with library developers.

### **Questioner: Brian Ford**

*Who pays for each analysis? Do Doctors keep their own copy of each image (as well as the copy in the system database), and are the patients given a copy? How is this provided?*

#### **Vania Boccia**

At present the project has an experimental status - it is sponsored from the two basic research projects I cited in the talk and nobody pays for any analysis. In this phase the doctors have some authorized test images stored in their database at the hospitals. Regarding to the personal copy of the images I don't know if patients have it; this matter is managed directly by the doctors.

### **Comment: Pat Gaffney**

*Transporting images to patients in order satisfy the UK Data Protection act, comes under the category of MOVING data, which the speaker mentioned. Most Western countries have restrictions on MOVING medical patient data. What the patient does with his or her data is not the concern. It is the movement that must be secure.*

**Vania Boccia**

The data movement in the environment is granted by the secure channel provided by the Globus GridFTP protocol. Furthermore data about the patient identity is not present in the data moved. This information remains at the hospital database. Anyway, at present this problem has not been faced, but we are investigating local laws and how other research groups think to solve security issues.

**Questioner: Brian Ford**

*Why is the limit of 10 set on the iteration count for CG?*

**Vania Boccia**

To “cure” the problem's ill conditioning, iterative methods that have the so called *semi convergence* property are used. For these methods, there exists an optimal number of iterations that gives the least value of the residual at the solution. Numerical experiments gave the proof that the optimal iteration number for the CG algorithm is ten while for EM it is six.

**Questioner: Brian Ford**

*Presumably the physician can always seek a reprocess if he feels that fault correcting processes have not been sufficiently successful for his needs. Note the difficulty of comparing the two images in such systems.*

**Vania Boccia**

The doctor can require every time he wants to process again the data that have been already processed. He can for example ask for reprocess these data with different algorithms and make a comparison. This is possible and not difficult in actual version of the PSE. Output images are stored and there is a little search engine to find set of images to be compared.