SIMULGEO AND ITS APPLICATION FOR THE MUON BARREL POSITION MONITOR

Laurent Brunel
CERN (CH 1211 Genève 23)
and Kossuth University (Debrecen Hungary)

1. INTRODUCTION

The design process of the Muon Barrel Position Monitor of the CMS experiment for LHC is at the origin of the need of a software like Simulgeo.
Obviously, many technical solutions of the monitoring system were envisaged during the R&D period. For some simple systems that can be seen as a chain of optical instruments, it is easy to estimate the global performance "by hand". But as soon as one introduces redundancy and geometrical loops, it is very difficult to have a good estimation. In this case, in topography, the method used consists in making a careful modelling of the system, in writing the "design matrix" [1] and, from the known errors, in calculating the unknown errors. Some specific programs [2,3,4] were written to solve the mathematical aspect. The problem is that the construction of the design matrix strongly depends on the studied system and such an effort could be made only for a limited number of systems. The software called "Simulgeo" started to be developed in 1995 [5] in order to allow the study of many systems. The idea of Simulgeo is to automatically make the modelling of a system and automatically construct the design matrix. The system is described in an easy way thanks to a special language. There is in principle no limitation for the size and the complexity of the system. A document [6] explains in details how is designed this software and how to use it. Simulgeo can be downloaded from the CMS server [7].
This paper makes in part 2 an overview of the possibilities of Simulgeo, in part 3 it presents the standard objects. In part 4, it explains the mathematical basis and in part 5 the computing aspect. In part 6, it shows an application to the Muon Barrel Position Monitor project and, in part 7, it mentions other projects where it has been used.

2. MAIN FEATURES OF SIMULGEO

2.1. Structure of Simulgeo

SIMULGEO is organised as following (see figure 1). The user communicates through an input text file, output texts and a graphical output. The first layer takes care of building an internal model in memory from the description of the input text file. The second layer creates the matrices used for the calculation. And the third layer makes the matrix operations and the resolution of linear systems of equations (it can be a standard library).
The new aspect of this work is the first layer: it takes care of the modelling of an opto-geometrical system and improves the productivity of the sytem designer.

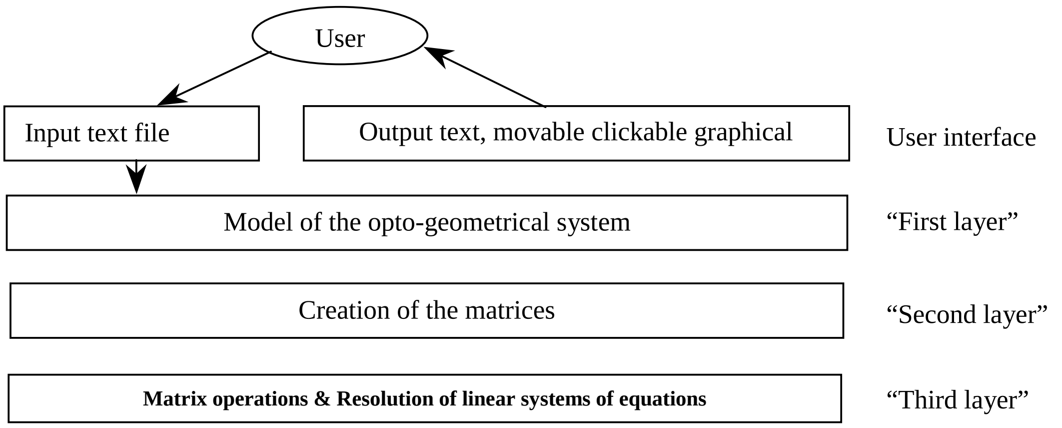

Figure 1: structure of SIMULGEO. The layer taking care of the model (first layer) undertstands a special language and automatically manages the mathematical calculation.

2.2. A language for the description of a geometrical system.

The firts layer of Simulgeo understands a language for the description of a geometrical system. In general, defined objects and their parameters (usually their co-ordinates) can describe any geometrical system. Some of the objects are sensors that are able to measure a physical value (for example a distance, the co-ordinates of a spot in a sensor matrix, etc…). The input text file of Simulgeo allows the user to describe precisely the objects and the parameters thanks to a certain language that we can call the "simulgeo language".
A very limited number of keywords is imposed. The majority of names and types are declared by the user himself. The structure of the language is imposed. This structure is hierarchical or in other words following approximately the logic of russian dolls. Hence, the main system is declared as containing other sub-systems which themselves are declared as containing sub-sub-systems and so on untill the standart predeclared objects.
The standart objects must contain a list of parameters in which significance must be found in the documentation (for example the 3 local co-ordinates of a point). Some of the parameters can be declared as known or calibrated with a certain precision and some others can be declared as unknown. The precision of the measurements must also be indicated.
In addition, some particular objects called measurers can provide measurements (a list of output numerical values). The calculation of this measurements needs references to other objects

present in the system. For example a 2D sensor can measure a laser position with respect to itself (2 numerical values) and so needs a reference to this laser. Then, in the case of these particular objects called measurers, the user must provide also a list of measured objects references including naming, expected measurement value and precision.
Of course, the user must take care of designing a system with enough pertinent measurements for the purpose of calculating the unknown parameters. The user can perfectly design a redundant system. In this case, the system makes more measurements than the minimal number needed to measure the unknown parameters.

2.3. Possibilities of Simulgeo

Simulgeo provides 2 main features: simulation of the error propagation and reconstruction.
The error propagation allows the users to estimate the precision of the unknown parameters knowing the precision of the measurements and the calibrated parameters. In the case of a redundant system, the precision of some calibrated parameters might be improved. One can speak about a “self calibrated” system. In this case, Simulgeo calculates the resulting precision of calibrated parameters and tells the improvement from the calibration measurement in percentage.
The reconstruction allows the users to introduce the measurements from a real hardware system. Then Simulgeo optimises the parameters in order to fit the closest model to the real measurements. The unknown parameter values are calculated and the calibrated parameter values might be corrected (in case of a redundant system).
The Simulgeo program might be used during all the phases of a project:

R&D process:

1. Accept or reject different configurations of the opto-geometrical system following the criteria of precision performance.
2. Make reliability studies. For example, see the effect of loosing a sensor on the global precision.
3. Make reconstruction during the laboratory tests.

Running phase of the opto-mechanical system:

4. Make reconstruction of the final system.
5. Provide the tolerances of the measurements.

The phases 1, 2 and 5 use the error propagation feature. The phases 3 and 4 use the reconstruction feature.

2.4. A short example of modelisation

Here is a very simple example to get an idea of the aspects of an input text file, and to see how looks like the graphical output. For more examples, refer to [6].
Let's assume that the user wants to evaluate the precision of a system which evaluates the 3D co-ordinates of a point from the measurement of its distance to 3 fixed points.
In this example, the precision on the distance measurement is 0.020 mm. The precision on the knowledge of the co-ordinates of the fixed points P1, P2 and P3 is also 0.020 mm.

The error propagation result given by Simulgeo is that the co-ordinates of the distancemetre "dist" can be known with a precision of σ=0.029.
See figure 3 the grahical output of Simulgeo for this small project and the input text file that must be given to Simulgeo is following.
Note that the distancemetre co-ordinates are tagged as "var": its indicates that they are unknown. The other parameters (co-ordinates) are tagged as "fix" since they are calibrated during, for example, a pre-survey of the 3 fixed points.
See figure 2 a graph showing clearly the hierarchical (tree-like) organisation of the input text file.

```
//few lines are missing here, for simplification
//Standard object types:
object  point  ent 3  coo
object  distancemetre    mes 1 point
/*Objects type created in this project*/
object system affineframeglobal point point point distancemetre
end
// THIRD PART
system system
point P1
      X    1000         0.020 fix
      Y    0    0.020 fix
      Z    0    0.020 fix
 point P2
      X    0    0.020 fix
      Y    1000         0.020 fix
      Z    0    0.020 fix
 point P3
      X    0    0.020 fix
      Y    0    0.020 fix
      Z    1000         0.020 fix
distancemetre dist
      {
           {    system_P1
                d simulated_value 0.020 }
           {    system_P2
                d simulated_value 0.020  }
           { system_P3
                d simulated_value 0.020  }
      }
      point centre
           X  100       100 var
           Y  100       100 var
           Z  0         100 var
end
```

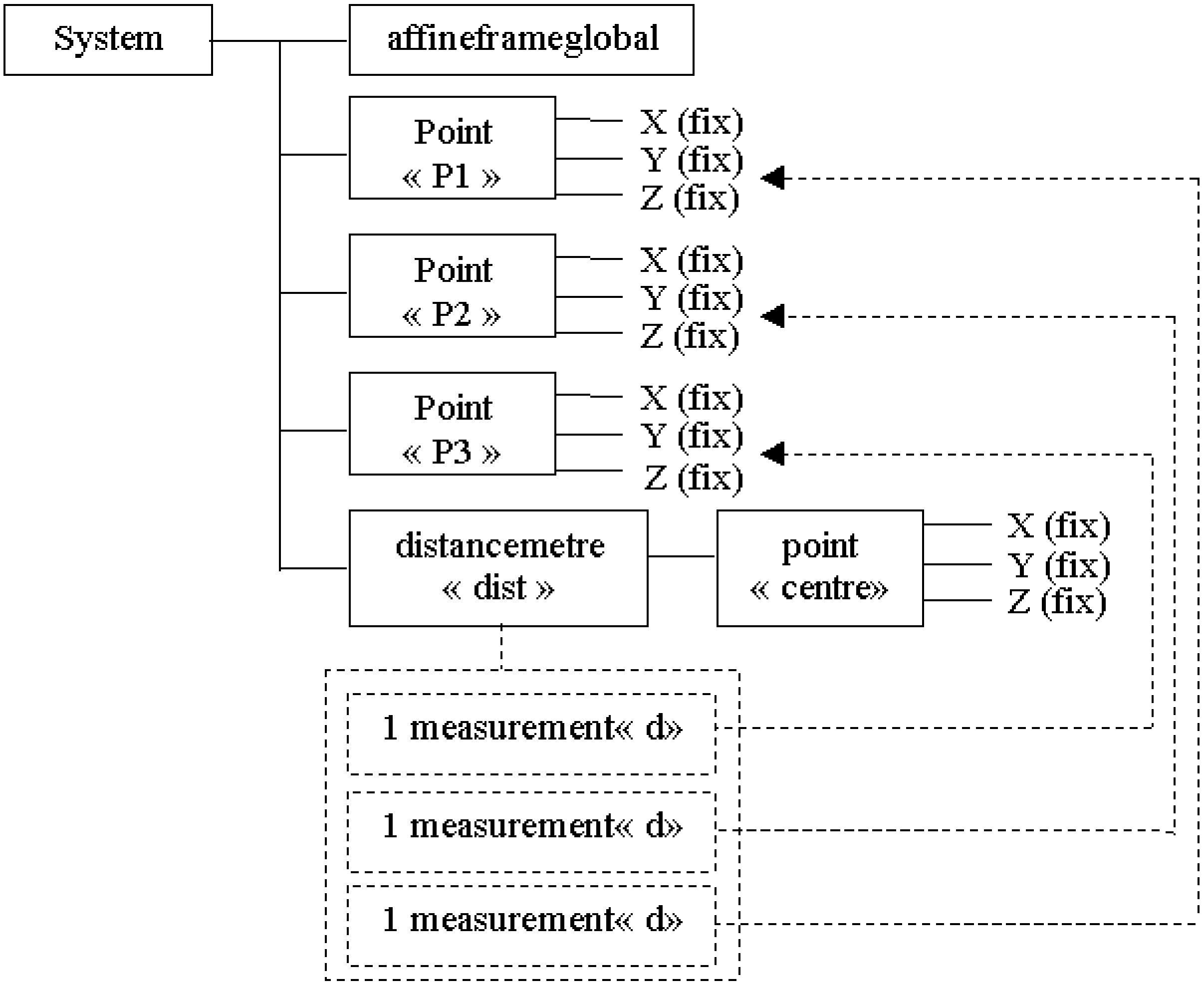

Figure 2: diagram of an example using "distancemetre". The tree-like organisation is shown here. The system contains an "affineframeglobal", 3 points and a distancemetre. The distancemetre contains itself a point and makes 3 measurements with 3 references. In each box are mentionned the type and the name of the object. The keyword "fix" means that the parameter is calibrated and "var" means that it is an unknown parameter.

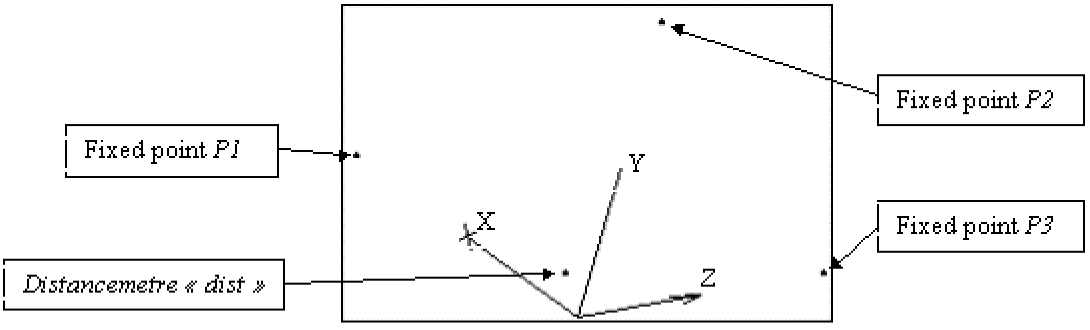

Figure 3: graphical output of an example using a "distancemetre". A "distancemetre" called "dist" measures the distance from itself to the point P1, P2 and P3. Simulgeo calculates the precision of measurement of the co-ordinates of "dist".

3. THE STANDARD OBJECTS

3.1. The input text file

In order to simulate its opto-mechanical system, the user has to describe it fully in a file called "input text file". The description of the full system consists in 2 phases. First, the structure of the system must be described and second, all the data needed to define totally the system has to be written (co-ordinates, precision, names, keywords). A certain structure for an optical object is called "geometrical type" or simply "type" in this report. The user can build new "types" by assembling other existing "types". A particular geometrical type must be defined by the user in each project: it is the geometrical type describing the structure of the full geometrical system that the user wants to study. This type must be called "system".
The input text file has 3 parts (see figure 4). The first part defines the object types, including the standard types (common to all projects) and of course the main object type that must be called "system". In the second part, (optional) the user can give a name to numerical values in order to use this name later in the description text. In the third part, the user has to detail all the parameter values, precision, etc, of the components of the system. The components of an object are listed in the hierarchical order.

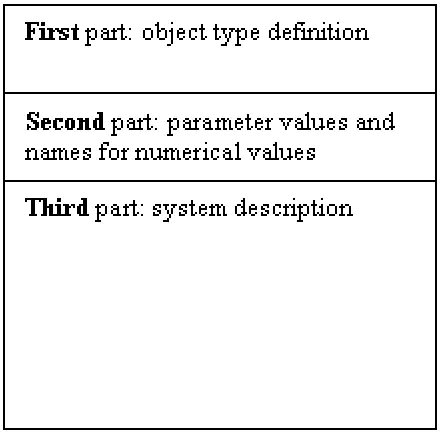

Figure 4: organisation of the input text file

3.2. Current list of standard objects:

At the moment, few standard object types are implemented. The user can reuse them in order to built his system.
point: represent a geometrical point. 3 entry parameters.
angles: represent a triplet of angles. 3 parameters
affineframe: represent an affine reference: a point and trivector. 6 parameters (3 co-ordinates and 3 angular co-ordinates).
direction: a couple of angles. 2 parameters
line: a point and a direction. 5 parameters.
Mirror: a point and a direction (the normal of the mirror). 5 parameters.

Detector: represents a 2D sensor. A point and 3 angles. 6 parameters. In addition, it makes measurements: the local co-ordinates of a light ray intersecting its surface. The light might be a laser beam or the beam created by a couple source/lens or a triplet source/mirror/lens etc…
The names of the object types (line, 2 points, line+mirror,etc..) measured by the detector must be indicated.
Clinometre: a couple of angles are needed to locate it. It also measures angles with respect to the vertical axis.
Distancemetre: a point able to measure its distance to other points. The name(s) of the objects (of type point) measured by the distancemetre must be indicated.

The details on these standard objects can be found in reference [6].

4. THE MATHEMATICAL BASIS

4.1. Introduction

Simulgeo uses classical formulas used in topography [1,2,3,4] to make the error propagation and the reconstruction. The calculation is based on the variance-covariance law and the "least square" method. An overview of the calculation is shown. Refer to [6] for more details.

4.2. Mathematical representation of the model

As it has been explained, Simulgeo uses the parameters given by the user to construct an ideal (perfect) representation of the system in memory. From this representation or model, Simulgeo is able to give a list of ideal measurement values obtained from the ideal sensors present in the ideal representation of the system.
Let's call X the vector containing a set of parameters and L the vector containing the list of measurements.
Then, it is possible to represent the optical system by a function F.
F: Space of the parameters ➔ Space of the measurements
X ➔ L=F(X)
Note: it is possible to represent the opto-geometrical system in a more general way F(X,L)=0 [1]. But the current version of Simulgeo uses only the more particular representation L=F(X).

4.3. Calculation of the error propagation

The error propagation calculation permits to get the RMS (Root Mean Square) of the parameters. For a given geometry of the analysed system, they mainly depend on the precision of the measurement values (RMS of the vector L).
Two assumptions are made:
Assumption 1: the statistic law of the errors is gaussian.
Assumption 2: the errors on the measurement values are not correlated.
The calculation of the error propagation is based on the variance-covariance law [1]. This mathematical method assumes that the statistic of the errors is gaussian. Then, the RMS of the error is the sigma of the gaussian. Another assumption is that the measurements are independant. The RMS of the parameters are calculated from the design matrix (A) and the weight matrix ($\sigma_0 P$). The design matrix A contains the partial derivatives of F (formula 1) and P is a

normalised diagonal matrix calculated from the RMS of the measurement values. The RMS of the parameters are extracted from the variance-covariance matrix Σ_{xx} (formula 2).

$$A_{ij} = \left(\frac{\partial F}{\partial Xj} \right)_i \qquad (1)$$

$$\Sigma_{XX} = \sigma_0^2 (A^t PA)^{-1} \qquad (2)$$

4.4. Least square fitting or reconstruction.

The other task of SIMULGEO is to find an optimal solution for the parameters in order to have the ideal measurements (the measurements made by ideal sensors of the ideal model of the system) as close as possible to the real measurements. The ideal model of the first iteration is built from the calibrated values of the parameters and from the approximate values of the unknown parameters.

The least square method is used. At the first iteration, the correction $(dX)_1$ is applied to the parameters X. $(dX)_1$ is calculated with the formula 3 knowing that the difference between the ideal measurements and the real measurements is called F. A new corrected X_1 is computed and a new model with a slightly different geometry is rebuilt in memory. Then another iteration is started. The iteration continues until that the norm of the correction vector $(dX)_k$ goes below a certain (small) value. Each calculated parameter comes with an error representing the quality of the regression (possible only in case of redundancy).

$$dX = (A^t PA)^{-1} (A^t PF) \qquad (3)$$

4.5. Optimisation using matrix operation adapted to sparse matrices

During the development of Simulgeo, it has been noticed that most of matrices operations involve sparses matrices. Some classical [8,9,10] algorithms has been implemented for the storage, addition, multiplication, system resolution of sparse matrices. A very significant decrease of the calculation time and memory use has been noticed. Nevertheless, in the case of very interconnected opto-geometrical systems, the last part of the calculation involves matrices loosing their sparsity. A detailled study is presented in reference [6].

5. COMPUTING ASPECT

The firts versions (1 to 5) has been developped in C for dos and unix operating systems. The last version (6) is fully developped in JAVA. It allows Simulgeo to work on any platform supporting java virtual machine (Sun, PC, HP, Linux,..). The java classes (binary code) of Simulgeo and some examples can be downloaded from the CMS web server [7].

6. APPLICATION TO THE MUON BARREL POSITION MONITOR

6.1. Presentation of the Muon Barrel Position Monitor

The CMS experiment (Compact Muon Solenoid) [11] is one of the experiments of the future Large Hadron Collider (see figure 5). Due to the size of this experiment and the expected movements of the sub parts, an optical position monitoring system is needed. This system (also referred as "alignment" system) [12] involves (see figure 6):

a. The internal alignment of the inner tracker which measures any deformation of the central tracker.
b. The link system, which transfers the position of the tracker to linking points located between the barrel and the end-cap muon regions.
c. The Muon Barrel Position Monitor and End-cap Position Monitor internal alignment that measures the positions of the muon detectors with respect to the linking points.

Our group has worked on the design of the Muon Barrel Position Monitor (see figure 8). The measurement in the case of the barrel system is achieved by measuring the positions of light sources fixed at each corner of the barrel muon chambers thanks to video cameras that are connected with the linking points. To do so, a geometrical network will be installed inside the CMS muon barrel volume. This network is based on stable mechanical structures (called MAB for "Module optique pour l'Alignement du Baril") holding mainly video cameras and optical point sources. This network is strongly (in a redundant way) connected both to the linking points and to optical point sources rigidly mounted inside the muon chambers. The high number of points to measure (the 1000 corners of 250 muon chambers must be located) implies the use of low cost sensors and light sources. The design strategy is to set a maximum number of interconnections in order to get the highest redundancy. The advantage of this strategy is to improve the precision (the same measurement is made more than once), the reliability (a part of the network can be damaged and the system can still provide co-ordinates) and provide a partially self-calibrating system.
Even if the system is fully interconnected, some sub modules can be identified. 2 types of modules can be considered. The first one is called "active plane" and the second one is called "passive plane" (see figure 7 also).
The "active plane" is a group of 4 MABs aligned along the longitudinal axis with the 2 external MABs connected to the inner particle detectors thanks to 2x6 lines on each side of the muon barrel (previously called "linking point"). Inside an "active plane" the 2 inner MABs are strongly connected to the outer MABs by 8 optical lines going through the muon chambers. The longitudinal co-ordinate of each MAB is measured thanks to cameras observing a long "ruler" holding other optical sources.
The "passive plane" is a group of 2 MABs also connected together by 8 optical lines going through the muon chambers. The "passive plane" is not directly connected to the "link lines".
The interconnection between 2 longitudinally neighbour MABs is done thanks to the following trick. On the first MAB, a video camera observes 2 or 4 optical sources fixed inside the 1 or 2 muon chamber(s) placed between the 2 MABs. On the second MAB another camera is observing the same optical sources, that are emiting light both side. This observation of at least 2 common sources by the 2 cameras makes possible the geometrical connection between the axis of these 2 cameras.

In addition, the MABs are equipped with clinometers which permits a good control of the possible torsion movements of each « plane ».
One can notice that there is very redundant (8 lines) connection of the MABs inside a "plane".
The "passive planes" must be connected to the "active planes". This is the role of the "diagonal connections". They connect the planes together in order to create a global "rigid" body. This "diagonal connection" (see figure 7) uses the triangulation technique: on a MAB belonging to a "passive plane", a camera holding 2 optical axes (the angle between the 2 axes is carefully calibrated) observes 2 optical sources mounted on 2 MABs belonging to the next "active plane". Since the distance (longitudinal) between these 2 sources is known (as 2 connected parts of the "active plane"), a simple triangulation allows the calculation of the transverse distance from plane to plane. As shown in figure 7 this "plane to plane" connection is done 4 times between each "plane" and closes itself in a circular network which improves again the redundancy.

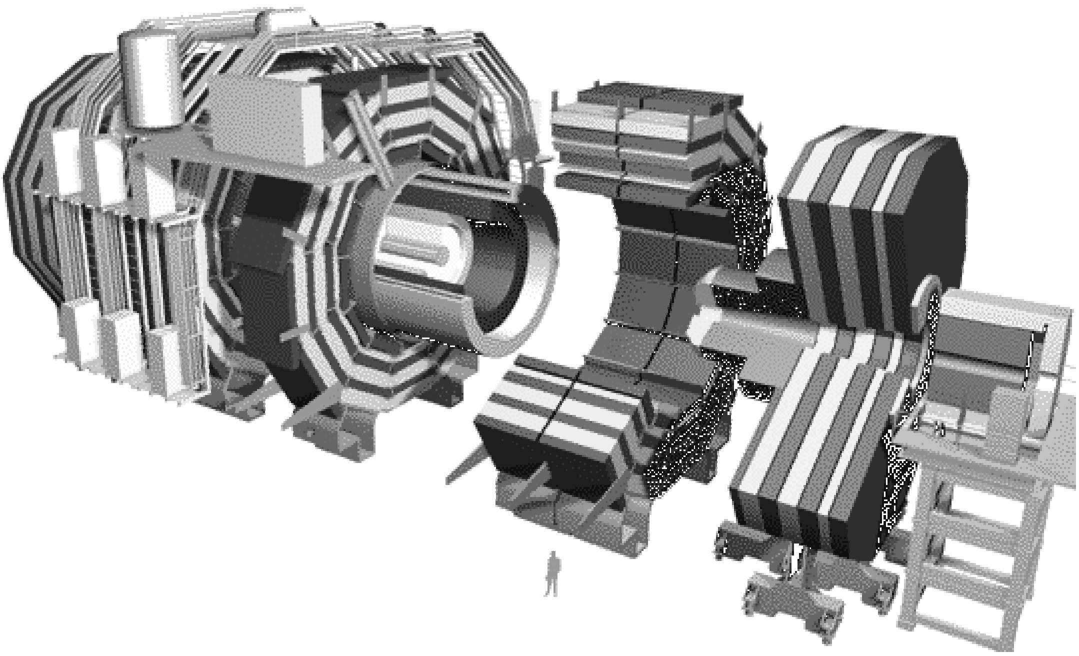

Figure 5: three dimensional view (exploded) of the CMS experiment for LHC [from CMS web site]. The detectors are mounted around a powerful solenoidal magnet. Inner tracking detectors and calorimeters are mounted inside the magnet. The muon detectors are mounted around in 4 layers, inside an iron yoke. The experiment is an assembly of 5 central wheels and 2 end cap that can be individually displaced during shut-down.

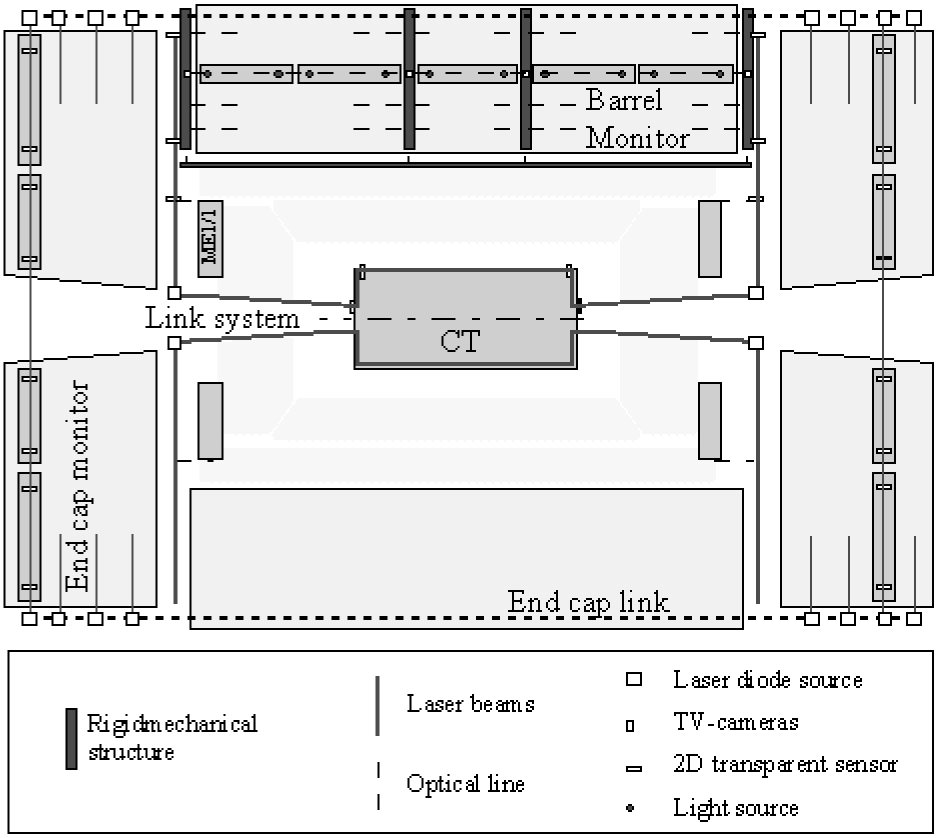

Figure 6: cut view of the full optical monitoring system of CMS. There are 4 different modules. The inner tracker has an internal monitoring system. The muon detector is splitted in 2 modules: the barrel and the end-caps. The module called "link system" makes the connections between the 3 other modules. The case study of this report is the muon barrel position monitor.

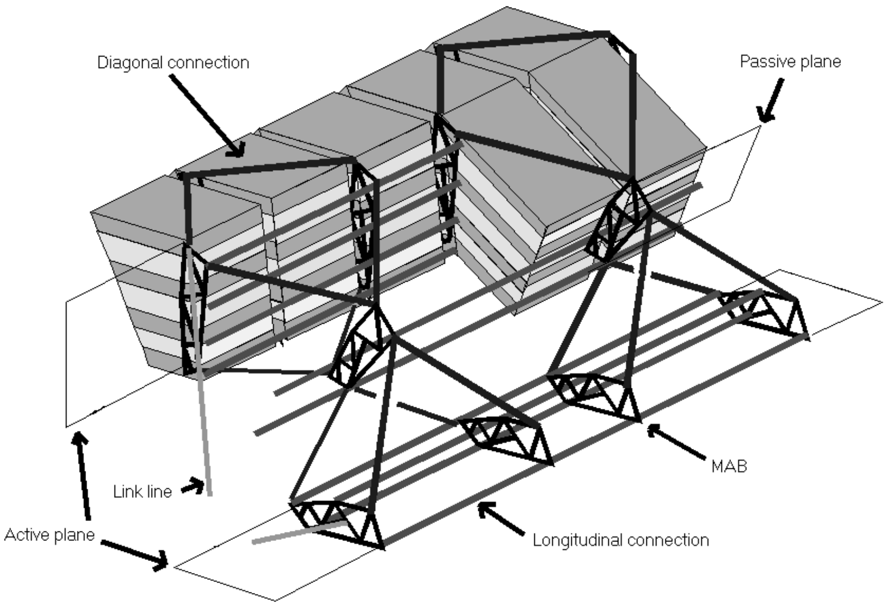

Figure 7: view of 2 “active planes” , 1 passive plane and the diagonal connection between them.

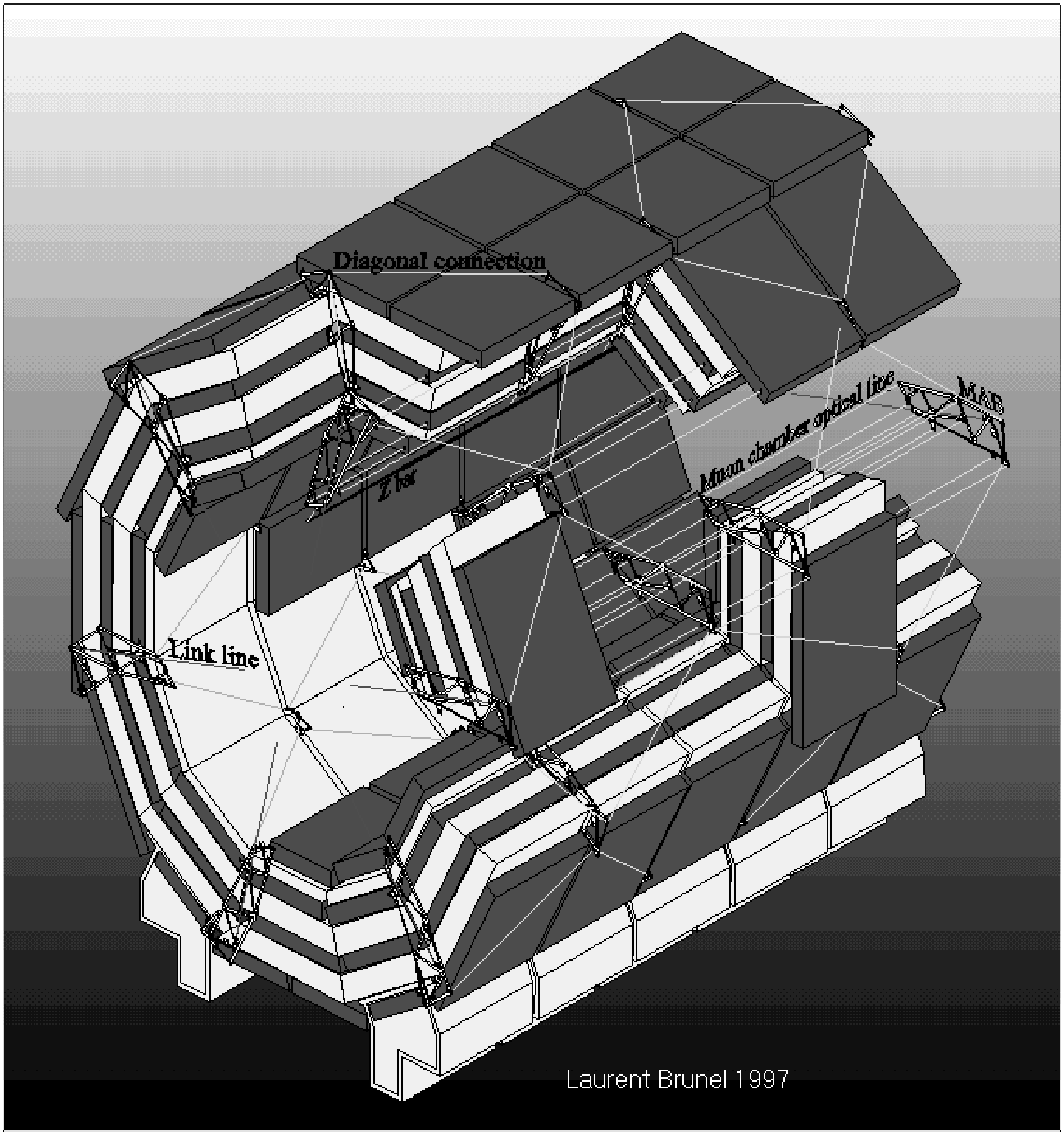

Figure 8: view of the Muon barrel and its position monitor. The muon chambers are located in 4 layers. They are not placed in a projective way (they overlap) in order to improve the hermeticity of the muon spectrometer (detect a maximum number of muons). 36 rigid structures called MABs are inserted inside the barrel. The external MABs are connected to link lines going from the inner detector. The other (internal) MABs are geometrically connected through longitudinal optical lines and "diagonal" optical lines.

6.2. The use of Simulgeo on the Barrel Position Monitor

Simulgeo has been intensively used during the design process of the barrel Position Monitor. Three studies with Simulgeo have permitted to evaluate the performance of the full system, presented in the CMS Muon technical design report [12,14] (1997). These studies are the following:

1. Error propagation study of the active plane
2. Error propagation study of the passive plane
3. Error propagation study of the MAB network (gathering 6 “active planes” and 6 “passive plane”)

In the cases 1 and 2 (see figure 9 the graphical outputs of Simulgeo), Simulgeo has been used to estimate the "rigidness" of the body "plane". In other words, from the knowledge of the resolution of the sensors, the precision of calibration procedures, the mechanical stability of the MAB structures, Simulgeo evaluates the precision of measurement of the co-ordinates of the optical sources hold by the muon chambers with respect to the reference frame of the "plane". In both case, the reference is attached to the centers of the 2 external MABs. Each "plane" has enough internal measurements to be geometrically stand-alone and can be considered as a full rigid body.

In the case 3, one simulate 6 “active planes” and 6 “passive planes” considered as rigid bodies equipped with bi-axis cameras and optical point sources making the diagonal connection (see before). The external MABs of each “active plane” is assumed to be connected with the inner particle detector (through the “link system”) with a precision of 100 microns. The reference of this simulation is the one of the “link system”. The influence of the diagonal interconnection is studied here. The results are plotted figure 10. One can notice that the diagonal inter-connections improve sensibly the precision of the “link system”.

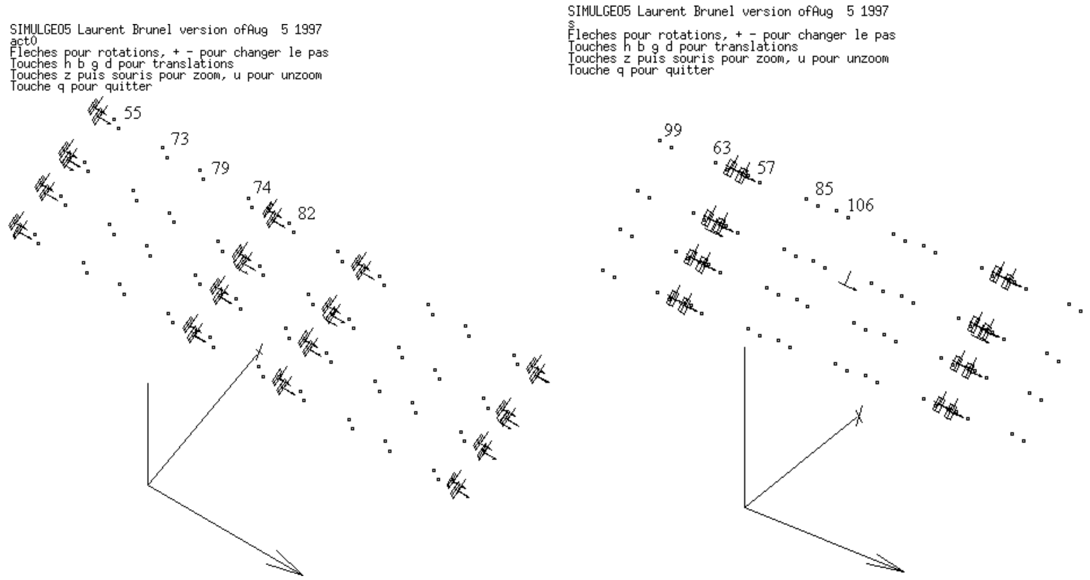

Figure 9: graphical outputs of Simulgeo for the simulation of an "active plane" and a “passive plane”. The numbers that are added indicate the precision of knowledge of the optical sources transverse co-ordinates. The reference frame is attached to the centre of the outer MABs.

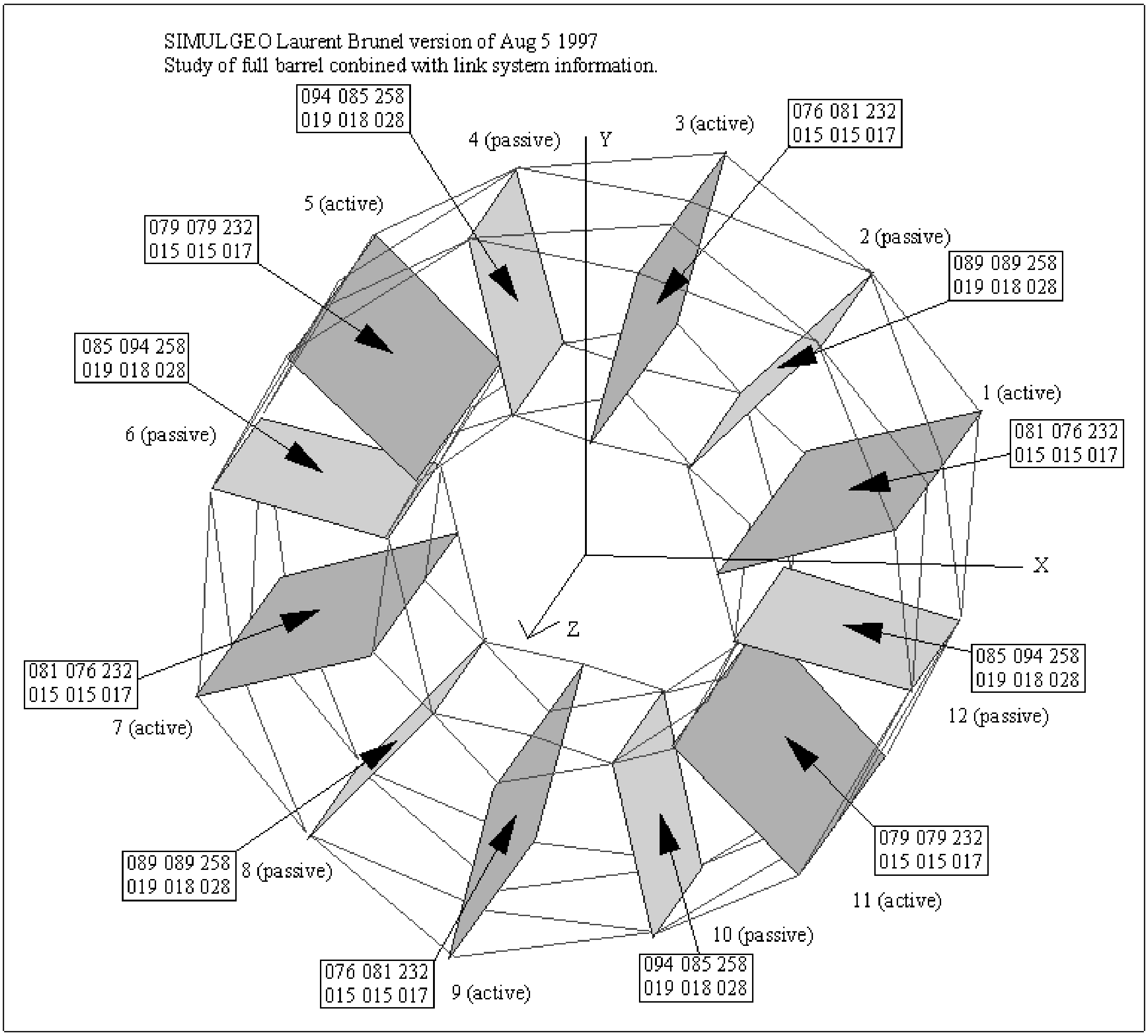

Figure 10: error propagation study of the reinforcement of the “link system” provided by the diagonal interconnections between the “planes”. Each box contain the resulting precision of knowledge of the position of each of the “planes”. The upper numbers are microns (x, y z). The lower numbers are angles in microrad (angle around x, y and z).

7. OTHER PROJECTS USING THE SIMULGEO SOFTWARE.

7.1. The inner tracker monitoring system

This system has been already mentionned in this report. Its purpose is to monitor the relative position between the elements of the central tracking detector of CMS [13]. Its present design involves video cameras looking at optical point sources mounted on the elements to be monitored. Several studies using Simulgeo has been made by this group [15]. They confirmed previous studies made with a software specificaly dedicated to this system [4]. In addition some laboratory measurements could confirm again the error propagation simulated by Simulgeo [15].

7.2. The CMS reconstruction software

An adaptation of Simulgeo (called Simulgeo++) is being designed for the specific constraints of the future CMS particle tracks reconstruction software called ORCA [16].

7.3. The "ME11" muon detector wheel

The "ME11" muon detector wheel is part of the muon end cap detector of CMS. A specific internal monitoring system has been designed in order to give the relative position of 36 muon chambers making a wheel all together [17]. This system is based on cameras and optical point sources. Simulgeo has been used to estimate of the performance of this proposal.

7.4. The Alice experiment for LHC

The ALICE experiment for LHC also needs to monitor the positions of its elements. Simulgeo has been used to start an evaluation of a system using lasers and transparent sensors [18].

8. CONCLUSION

In this report, the Simulgeo software has been presented. Its place in an opto-geometrical project has been shown. A simple example and its main features for the user point of view has been described. Some internal aspect has been also summurised.
Then, this paper has emphasized 3 examples of simulations using Simulgeo for the CMS Muon Barrel Position Monitor project. Project which is at the origin of this software.

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