DAS Departamento de Automação e Sistemas
CTC Centro Tecnológico
UFSC Universidade Federal de Santa Catarina

# Automated Simulation of Assembling of a Self-Optimized Optical System

*Relatório submetido à Universidade Federal de Santa Catarina*

*como requisito para a aprovação na disciplina*

***DAS 5511: Projeto de Fim de Curso***

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# Automated Simulation of Assemblying of a Self-Optimized Optical System

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Esta monografia foi julgada no contexto da disciplina
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# Resumo

Este documento é uma monografia do projeto de fim de curso de Engenharia de Controle e Automação da Universidade Federal de Santa Catarina. O trabalho aconteceu no Fraunhofer Institut for Laser Technology (ILT), entre Abril e Setembro de 2015.

Com mais de 400 empregados e mais de 19,500 m² de área total, o Fraunhofer Institut for Laser Technology é mundialmente um dos mais importantes centros de pesquisa no seu campo específico. As atividades cobrem um vasto alcance de áreas como o desenvolvimento de novas fontes de raio laser e componentes, metrologia de precisão baseada em laser, tecnologia de testes e processos de laser industriais. Isso inclui corte, furação, soldagem, e soldagem, assim como tratamento de superfícies micro processamento e manufatura rápida à laser. O Fraunhofer ILT é parte da sociedade Fraunhofer, com 66 institutos, 24000 empregados e orçamento anual de pesquisa de mais de 2 bilhões de euros. .

[ 1 ]

No Fraunhofer ILT foi desenvolvido este projeto de final de curso. Para construir um sistema automático auto otimizado de montagem para sistemas laser, uma simulação automática de montagem de sistemas óticas deve ser realizada. O trabalho é dividido em dois conjuntos principais de atividades.

O primeiro conjunto de atividades consiste em resolver o problema da ordem de montagem do sistema ótico. Uma estratégia de ordem de montagem que leva em conta as tolerâncias de manufatura de cada elemento é implementada em conjunto com um software de modelo de sistemas óticos, em uma maneira automatizada.

O segundo corresponde ao restante dos passos para implementar uma simulação de montagem automatizada, uma vez que a ordem já está decidida. Com uma simulação automática implementada, a estratégia de montagem é avaliada para uma variedade de sistemas óticos.

Este documento está organizado em 7 capítulos. O primeiro contextualiza e introduz o problema, e justifica a motivação para realização de tal projeto. O segundo capítulo introduz uma base conceitual a qual é necessária para a compreensão do trabalho, apresentando importantes conceitos, como o de tolerâncias em sistemas óticos e sistemas auto otimizados, por exemplo. O terceiro apresenta o estado da arte e outras soluções desenvolvidas para este mesmo problema. No quarto capitulo é exposto o primeiro problema e macro conjunto de atividades deste projeto, que é a escolha e definição de um critério para ordem de montagem das lentes em sistemas óticos. O quinto capítulo descreve a concepção de uma simulação automatizada da montagem de um sistema ótico, usada para avaliar também a estratégia definida no capitulo anterior. O sexto capítulo apresenta os resultados obtidos. Finalmente, o sétimo capítulo apresenta a conclusão do trabalho e apresenta algumas perspectivas futuras desse.

# Abstract

This document is a monograph of an end of course project of the Automation and Control Engineering course at the Universidade Federal de Santa Catarina. The work took place within the Fraunhofer Institute for Laser Technology, between April and September of 2015.

With more than 400 employees and more than 19,500 m² net floor space the Fraunhofer Institute for Laser Technology ILT is worldwide one of the most important development and contract research institutes of its specific field. The activities cover a wide range of areas such as the development of new laser beam sources and components, precise laser based metrology, testing technology and industrial laser processes. This includes laser cutting, caving, drilling, welding and soldering as well as surface treatment, micro processing and rapid manufacturing. The Fraunhofer ILT is part of the Fraunhofer-Gesellschaft, with 66 institutes, 24,000 employees and an annual research budget of more than 2 billion euros. [1]

In the Fraunhofer ILT it is developed this end of course project. In order to build an automated self-optimizing assembly system for assembling of laser systems, an automated assembly simulation of an optical system (working together with an optical model) has to be realized. The work was divided into two main sets of activities.

The first set of activities consists of solving the problem of choosing the assembly order of the optical system. An assembly order strategy that takes in account the manufacturing tolerances of each optical element is implemented in conjunction with an optical model software in an automated way.

The second corresponds to the rest of the steps to implement an automated assembly simulation, once the order is already decided. With an automated simulation implemented, the assembly order strategy is evaluated for a variety of different optical systems.

# Summary

# Chapter 1: Introduction

Laser systems today are used in a wide range of applications – DVD and blue-ray readers, barcode scanners, laser printers, laser based metrology, and in industrial processes such as cutting, drilling, welding and as well as surface treatment.

Today, the assembly of laser systems is dominated by manual operations constituting about 80 % of laser production costs (material costs are not considered) [2]. As a consequence of the ongoing globalization, strong international competition results in an increased variety of manufactured goods with short life-cycles. As countries with low labor cost induce strong pricing pressure, solutions for modern production systems have to be developed meeting high demands on flexibility and efficiency. In high-wage countries, the significant differences in input factor costs require a fundamental increase of the degree of automation to enable production at competitive costs. In addition, automation allows quality, reliability to be increased and working conditions to be improved. However, high degrees of automation often correlate negatively with the flexibility of production systems [3].

Also, investing into automation solutions is only profitable if the break-even point can be achieved within the lifetime of the system. Usually, high production volumes are required in order to achieve this. It is desirable to achieve the break-even point even for lower production volumes. This can be achieved through reduced planning efforts even for highly complex production scenarios under the influence of uncertainties, which is the aim of the research domain of ‘Self-optimizing Production Systems’ [4].

This end of course project goal is the building of an automated self-optimizing assembly simulation system for assembling of laser systems. The first part of it deals with the order the optical elements are assembled, taking into account its manufacturing tolerances. The second part is about the implementation of the automated assembly simulation, so that the order created in the first step can be evaluated. The simulation is also an important step towards the realization of a real self-optimizing assembly system.

This document is organized in 7 chapters. In the chapter 3 it is introduced the state of the art in the field of this work. Chapter 4 describes the algorithm for choosing an assembly order and its implementation. Chapter 5 describes the automated assembly simulation and how it was implemented. Chapter 6 presents the results of the work. Finally, in chapter 7 the conclusion and future perspectives about this work is given.

# Chapter 2: Conceptual Basis

This chapter describes some of the fundamental concepts and theories necessary to understand the project. The topics covered here are the concepts of tolerances in optical systems, tolerance sensitivity analysis,Merit Function, self-optimized systems, and finally the application of optimization in the assembly of optical systems. It is not objective of this work to discuss any of these concepts in deep detail level, rather just the necessary for comprehension of the work.

## 2.1: Tolerances in Optical Systems – Main Types and Typical Values

Manufactured Optical Elements are always different from the ideal ones, in many aspects. This deviation is expressed in the form of tolerances. The main types of tolerances in optical systems are:

**Material Properties:** The refractive index of glasses and its variation with wavelength, the dispersion, are subject to the chemical composition and manufacturing processes. [6]

**Element Tolerances:** Optical Elements (e.g. simple or achromatic lenses) are defined by the geometrical relations of optical and mechanical surfaces. Hence, tolerances for tilted and de-centered surfaces are either given with respect to the mechanical axis of an element or between optical surfaces. This is Ilustrated in Figure 1.

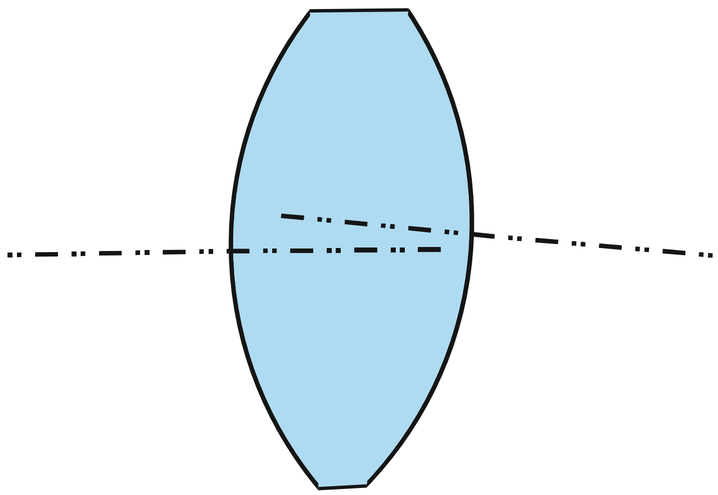

*Figure 1: Decenter Defined Between two Optical Surfaces.*

For arbitrary shapes, tilt and decenter of the surface axis are given with respect to a mechanical reference. In the special case of two spherical surfaces a unique axis of symmetry for both surfaces, the optical axis, can always be the mechanical axis. The alignment of this optical axis to the mechanical axis describes the centration of optical components. [7] It is probably the most important element tolerance and in general a vector quantity. In addition, element thickness is defined as the distance of surfaces vertices.

**Surface Form:** While element tolerances relate optical and mechanical axes, the surface form error describes the difference between a real surface and a reference surface in alignment. The form error is measured along the optical axis and denoted surface sag: interferometric measurements are commonly applied to determine the surface form deviations and led to the specification of interference fringes for tolerancing on ring measuring the sag units of half the wavelength of the test light (typically 589 nm) (Figure 2).

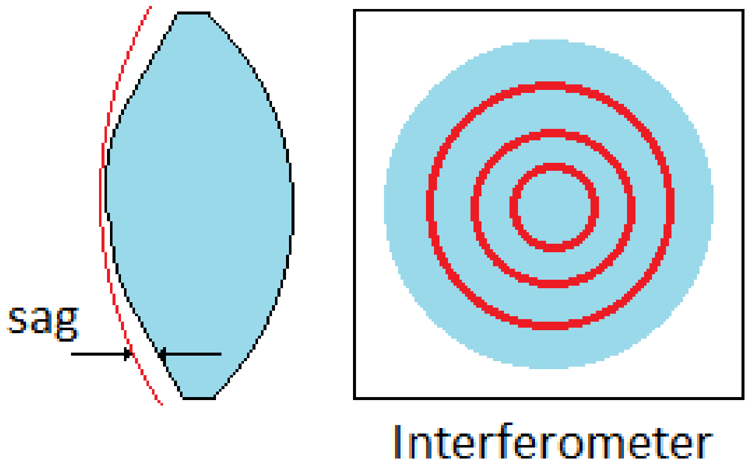


*Figure 2: Comparison between surface and reference surface in red. The surface sag causes fringes to appear in the interferometer.*

Form errors of aspheric surfaces are often difficult to describe due to large differences to a reference sphere. The classical definition of an aspheric surface as given e.g. in [8] is not very suitable for tolerancing, as the coefficients do not have a representative meaning. Assigning tolerances is hence very difficult.

**Mechanical Tolerances:** During Assembly, optical elements and mechanical mounts are brought together. As assembly typically has a certain amount of play between lenses and mounts, lens positions are not necessarily very well defined. The resulting tolerances are decenter, tilt and axial shift of entire elements with respect to a mechanical reference axis. Two effects are of particular interest: a variation in element thickness can reduce an adjacent air space, the distance to the next optical surface. Which distance serves as an adjust needs to be carefully determined from the mechanical design. This is often difficult in preliminary design stages when neither the optical nor the mechanical design is fixed. In addition, rotationally symmetric lenses can roll on them mount such that a spherical surface will stay in place as it has an infinite number of symmetry axes [9]. Hence, opto-mechanical tolerances require a great deal of attention and largely depend on the actual layout.

### Typical Commercial, Precision and Limit Tolerance Values

In order to limit the deviations of constructional parameters to an allowable range, tolerances are specified on engineering drawings. The specification of tolerances is regulated by the international ISO 10110. Table 1 summarizes typical tolerance values from commercial precision to a typical manufacturing limit. Higher precision can be achieved with specialized equipment.

| Tolerance Type | Tolerance | Unit | Commercial | Precision | Typ. Limit |
|---|---|---|---|---|---|
| Optical | Curvature/Radius | % | ±0,2 | ±0,1 | ±0,02 |
| | Curvature/Radius | Fringes | 5 | 3 | 1 |
| | Irregularity | Fringes | 2 | 0,5 | 0,2 |
| | Center Thickness | mm | ±0,150 | ±0,05 | ±0,010 |
| | Scratch-dig | (MIL) | 80-50 | 60-40 | 20-10 |
| | Surface sag | mm | ±0,050 | ±0,025 | ±0,015 |
| | Index | % | ±0,001 | ±0,0005 | Melt Data |
| | Dispersion | % | ±0,8 | ±0,5 | Melt Data |
| Mechanical | Air Space | µm | 50 | 12 | 2,5 |
| | Centering | arcmin | 6 | 1 | 0,25 |
| | Diameter | µm | 100 | 25 | 6 |

*Table 1: Tolerances of lens parameters for different levels of manufacturing precision [ 10 ] [ 11 ]*

The above tolerances hold true for grinding and polishing of lenses of 25,4 - 50,8mm diameter and have evolved over time. Surveys conducted by Plummer in 1979 [ 12 ] and Fischer in 1990 [ 13 ] report tolerances that were approximately a factor of two larger than the values depicted in Table 1. The surface tolerances of polymer lenses fabricated by injection molding are typically larger by a factor of ten, while center thickness tolerances are comparable [ 14 ].

It is also important to mention that the tightest are the tolerance limits, the more expensive it is to manufacture. This relation can be modeled approximately by an exponential curve, as shown in the Figure 3:

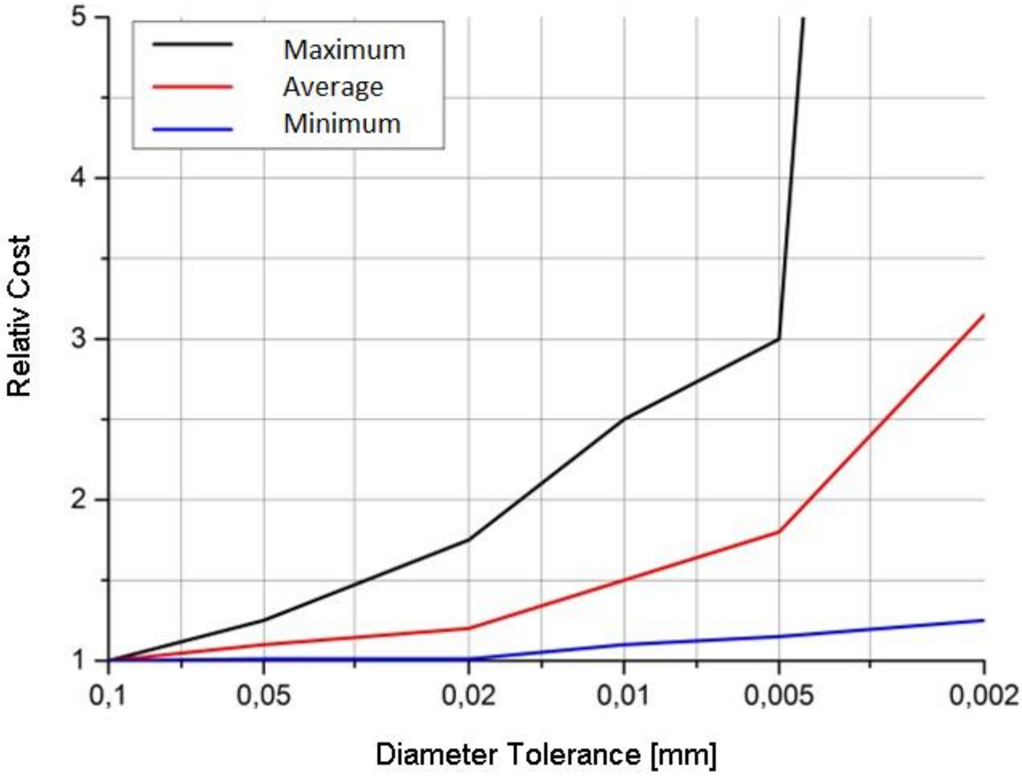


*Figure 3: Relative Cost of Diameter Tolerance Values. Upper curve is maximum, middle is average and lower is minimum*

## 2.1: Tolerance Sensitivity Analysis in Optical Systems

Tolerance Sensitivity Analysis is used to determine the impact of each individual tolerance in a chosen criterion. For each tolerance it is assigned an interval between maximum and minimum value. Then the analysis goes as it follows: The first tolerance to be analyzed is set to its minimum value, and the difference in a given criterion, which can be for example, the approximated radius of the beam, is associated with this tolerance’s variation to its minimum value. Then it is set to its maximum value, and the change in the beam radius is associated with this tolerance maximum value. The process repeats itself for all the tolerances to be analyzed. It is important to notice that while one tolerance varies the others values are set to zero. Each tolerance influence is analyzed independently.

## 2.2: Merit Function

It is a mathematical function used here to represent the optical quality of the system:

$$M^2 = \sum_{i=0}^{n}(v_i - t_i)^2$$

Where:

$M$ - Is the value of the merit function

$v$ - Is the actual value of an operand

$t$ - Is the target value of an operand

It can be noticed that the closer some operand is to its corresponding target value, the closer the Merit Function value gets to 0. Also, because the difference between target and actual value is squared, any deviation results in an increase positive value of the Merit Function.

Setting desired targets for specific operands in an optical system allow us to evaluate how far the actual values are from them.

## 2.3: Self Optimized Assembly

Self Optimized Assembly is a way of reducing planning efforts, thus increasing a systems autonomy and capability to deal with uncertainties that occur during the process of assembly. These uncertainties in optical systems appear in the form of manufacturing tolerances.

One key part to implement a self optimized assembly system, is to make the product function oriented – rather than just planning some fixed product geometry, some indicators like the laser beam quality are taken in account. The quality of the system is expressed in a merit function. When we decide some of the values of the merit function as variables, we give the system some degrees of freedom that can be used in order to achieve an optimum minimum value of the merit function. In this work, the decenter in the x and y directions and tilt in x, y and z directions are set as variables. Doing so, a merit function minimum is found through the merit function optimization, and the values of decenter and tilt are defined, which correspond to an assembly position.

Using that approach, the system can adapt itself to incoming uncertainties, and planning is done while the all actions are being performed, rather than before.

# Chapter 3: State of the art

In the following chapter shows a brief overview in the field of automated assembly of optical systems. Two different solutions are presented, and its operations, scope and main characteristics are exposed.

## 3.1: Automated Alignment of Fast Axis Collimator Lenses for High Power Diode Laser Bars

One solution to the problem of aligning Fast Axis Colimator lenses (FAC) is already present in the literature. This solves the problem of colimation of the beam, for one specific kind of laser in one direction.

In order to do so, an alignment algorithm is used, which is derived from a beam propagation model based on wave optics. The power density distribution is modelled as a function of five dimensional FAC displacements. The relations are investigated and formulated as unique and invertible functions. The algorithm considers diode laser displacement, pivot point misalignment as well as limited resolution and errors of the multi axis positioning system. The alignment accuracy and positioning errors of the positioning system are considered. The number of iterations is limited to five in order to decrease the overall alignment duration.

The algorithm is experimentally validated with two types of diode laser bars (808 nm and 940 nm center wavelength) and two types of FAC lenses (910 µm and 1500 µm focal length). Figure 4: Demonstrator system for testing the automated alignment of FAC lenses. The FAC lens is aligned in front of the diode laser (DL). The FAC lens is mounted in a mechanical gripper on top of a 6-axis positioning system *[ 16* ] Figure 4 shows the demonstrator system

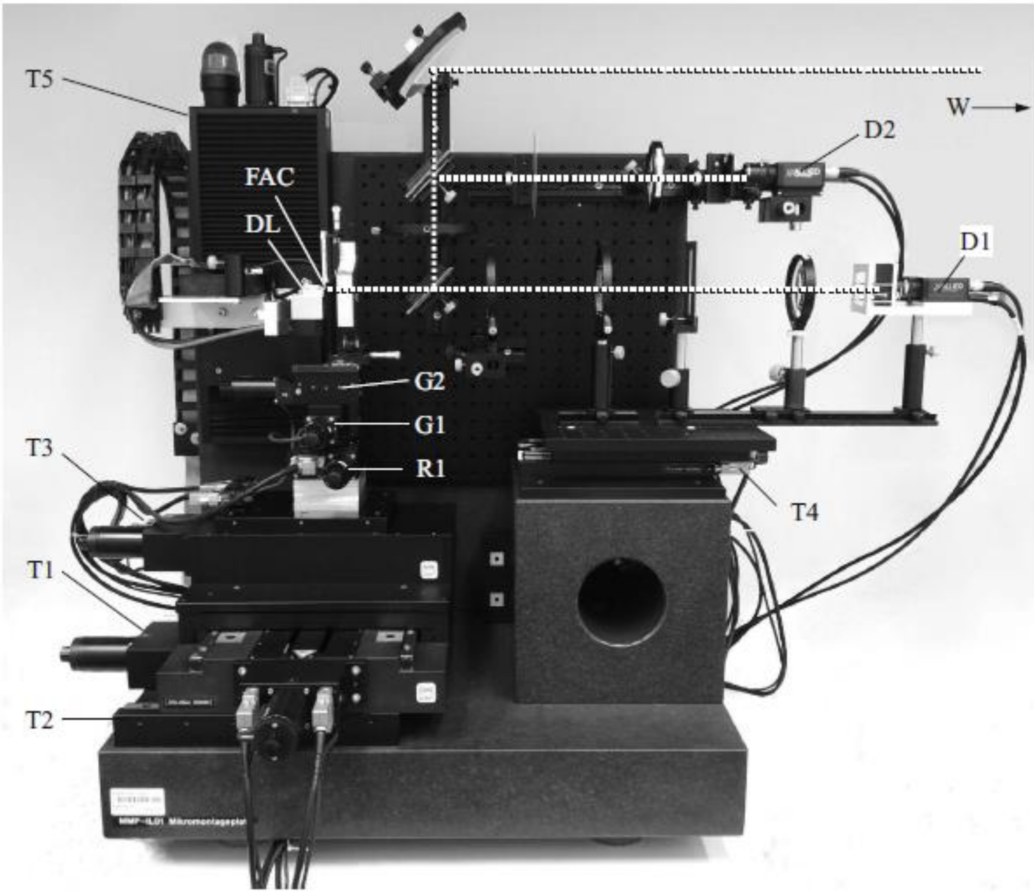


*Figure 4: Demonstrator system for testing the automated alignment of FAC lenses. The FAC lens is aligned in front of the diode laser (DL). The FAC lens is mounted in a mechanical gripper on top of a 6-axis positioning system [ 16 ]*

In a first step the FAC is manually aligned ten times. The average final FAC position is marked as the set point for the algorithm. Starting from this point the FAC lens is arbitrarily misaligned in five axes in a range of ±50 µm and ±0,1°. In the next step, the automated algorithm is executed to calculate and correct the misalignments. The procedure is repeated 50 times for every combination of components

The averaged translational misalignment of all investigated combinations amounts to 0.8 µm referred to the suitable positions achieved in manual alignment processes. The process reproducibility is increased by 70% compared to manual alignment. The averaged rotational misalignment amounts to less than 0.01 degree. The process duration amounts to 20-25 seconds. [17] Although It is an effective solution, its scope is still limited to one specific kind of lens, used with an specific kind of laser. Also, it requires a good alignment from the start, something that is not always available in the first place.

## 3.2: Automated Packaging Platform

An automated packaging platform is developed by CyOptics, Inc. for the assembly and test of high performance active component packages, using three robot assemblers. The following text provides an overview of the operation of working robotic assemblers in the manufacture of optical components.

The first robotic assembler, an optical sub-assembly assembler is designed around a high speed silicon optical bench where laser or detector chips, micro-lenses, and passive components are picked up, precisely placed, and finally bonded using solder or epoxy onto the silicon optical bench. The optical sub-assembly is tested using an automated tester and burned-in using batch processing after which it is ready for installation into an optical component package body. Figure 5 provides several examples of the optical sub-assembly assemblies done using this assembler in routine production.

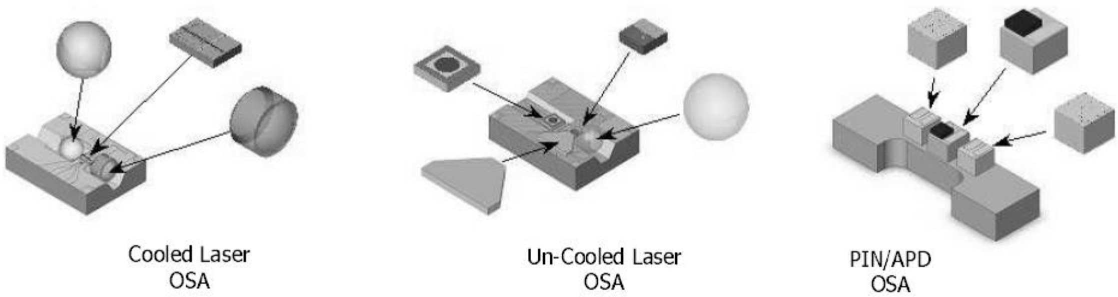


*Figure 5: Examples of Optical Sub-mount Assemblies*

The second robotic assembler, called a package assembler, is designed to install, align, and bond the burned-in optical sub-assembly into the package body, and attach the electrical RF connections. Similar to the optical sub-assembly assembler, this robot performs its tasks passively, without powering the active components. Figure 6 shows a photograph of the package assembler in action.

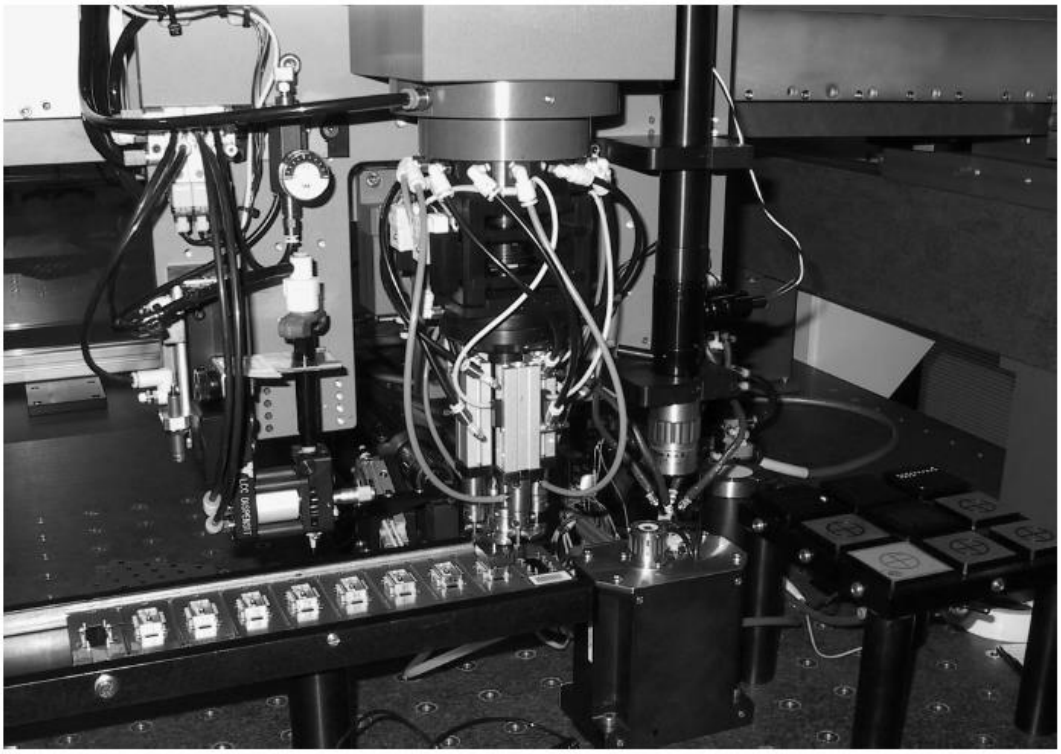

*Figure 6: Photograph of CyOptics Package Assembler Arm and Tool in Action [ 18 ]*

Following hermetic sealing of the package, the module is ready for the final active alignment of a single-mode fiber assembly. This is the last step of the assembly process, and is done using the third robotic assembler, called the fiber assembler. The attachment can be performed using either epoxy or laser welding.

In order to track, control, and monitor all the automated processes for these three assemblers, a smart and self-learning data base system is used. Key process parameters and results are controlled and monitored by the assembler. These include, for example, parts identification and incoming properties, device and lens positions, amount of bonding materials, and bonding force, temperature and time.

[ 18 ]

It is a solution that include a bigger variety of cases than the presented in the previous subchapter. However, the assembled optical systems still have to be designed taking in account necessary requirements like using the silicon optical bench.

# Chapter 4: Assembling Order Strategy

When assembling an optical system, the first important aspect to be defined is the order which the elements will be mounted. It is reasonable to presume that a particular order can impact the optical quality of the final product. Based on pre-existing literature, a theory was proposed, and it was developed an strategy for defining an assembly order, based on the optical elements manufacturing tolerances.

The first part of this project was to find a way to implement this strategy in a simulation altogether with the current used optical modeling software. In this chapter it is presented the algorithm and the steps necessary to its implementation.

## 4.1: The Tolerance Based Assembling Order - Overview

The main idea behind this assembly order is that taking into account the manufacturing tolerances corresponding to each element, and its impact on the quality of the system. Choosing the elements with higher impact on the optical quality of the system to be assembled first would allow the changes caused by their respective tolerances to be compensated when mounting the next elements. The Algorithm is summarized in the *Figure 7*:

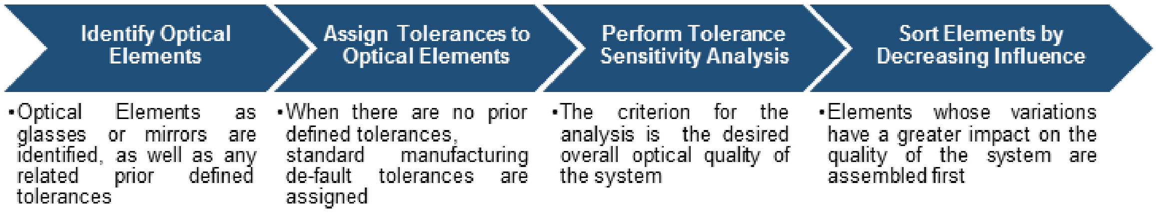


Figure 7:Assembling Order Strategy

**Identify Optical elements**:

For the scope of this project, two main kinds of optical elements should be identified: the mirror and the lens. These elements could assume the geometric forms of spherical, plane (in the case of mirrors) and toroidal (in the case of lenses). Also, cemented lenses, compound of two or more lenses, should also be included. Also are identified any tolerances related to these elements

**Assign Tolerances to Optical Elements:**

The tolerances used were, as element tolerances are the curvature radius of the elements, in the case of spherical or toroidal components, and the center thickness, in the case of lenses. Mirrors in the ideal case are considered just as a surface, and its thickness is null.  The mechanical tolerances used were decenter in the X axis, decenter in the Y axis, Tilt in the X, Y and Z axis. In Optics, conventionally the Z axis follows the beam direction, the Y axis is vertical axis pointing up, and the X axis follows the right hand rule in relation to the others. When the tolerances were not defined prior to the assembly simulation, the default commercial values of the Table 1 were assigned to the elements.

**Perform Tolerance Sensitivity Analysis:**

A tolerance sensitivity analysis is performed taking into account each tolerance of each element, and its defined minimum and maximum values. The result of the analysis is the change of the criterion for each minimum and maximum value, for each tolerance. As criterion, it is used a Merit Function which evaluates the desired optical quality of the system.

**Sort Elements by Decreasing Influence:**

First, the influence of each element has to be determined. This was done in the following way: all the criterion changes corresponding to tolerances of a given element were squared and summed. The element with a higher sum is defined as the one with bigger impact on the optical quality of the system. The values were squared so that two changes in equal magnitude but in opposite directions would sum themselves, rather than canceling each other.

## 4.2: Implementation

The implementation of this solution was realized using two different softwares. The first is called Zemax. It is a software that is used for ray tracing and optical design, and it was here used to implement optical models of the optical systems. This software was chosen because it can represent well a variety of optical systems that are in the scope of this project, also because it is already largely used in the Fraunhofer ILT,  so many of the employers are already familiar with. This means that the work developed in this project could be more easily reused or extended, saving a significant amount of time and money that would be necessary for training people to use a different software.

In addition, it was used the java programming language, together with a special communication protocol, the DDE (dynamic data exchange) in order to change information with Zemax and build a program that can automatically execute all operations necessary for the realization of the sorting algorithm. The java programming language was chosen because it was, within the options available that could also had the communication protocol with Zemax, the one that the people working on this project were most familiar with, so having the same advantages mentioned before concerning the choice of Zemax.

Now first, a description of the fundamentals of the Zemax will be explained, and the necessary steps for implementation of the assembly order strategy. Then, it is described how this automation was projected and implemented in the form of a java program.

### 4.2.1: The Assembling Order Strategy in Zemax

Prior to the explanation of how this was implemented, a basic functionality of Zemax has to be described.

The data about distinct optical elements is inserted in the Lens Data Editor (Figure 8: Zemax Lens Data Editor): The Optical components are modeled in the lens data editor the form of surfaces. The program calculates the position and orientation of a set of rays, based on the optical and geometrical properties of each surface. Each surface position is defined by an offset thickness of the previous surface. They can represent for example air, transparent glass, mirrors or changes of coordinates.

| | Surf:Type | | Comment | Radius | Thickness | Material | Coating | Semi-Diameter | |
|---|---|---|---|---|---|---|---|---|---|
| 0 | OBJECT | Standard ▾ | | Infinity | 2700.000000 | | | 0.000000 | U |
| 1 | | Standard ▾ | | Infinity | 10.000000 | | | 1.036724 | U |
| 2 | (aper) | Toroidal ▾ | | Infinity | 2.500000 | SF11 | | 1.500000 | U |
| 3 | (aper) | Toroidal ▾ | | -20.000000 | 50.000000 | | | 1.500000 | U |
| 4 | STOP (aper) | Toroidal ▾ | | 20.000000 | 2.500000 | SF11 | | 1.500000 | U |
| 5 | (aper) | Toroidal ▾ | | Infinity | 70.000000 | | | 1.500000 | U |
| 6 | | Standard ▾ | | Infinity | 50.000000 | | | 600.000000 | U |
| 7 | | Standard ▾ | | Infinity | 50.000000 | | | 600.000000 | U |
| 8 | IMAGE | Standard ▾ | | Infinity | - | | | 600.000000 | U |

*Figure 8: Zemax Lens Data Editor*

The data about the tolerances, used as input for the tolerance analysis is in the Tolerance Data Editor (Figure 9). Each tolerance is represented by a tolerance operand, which refer to a certain surface inserted in the Lens Data Editor.

| | Type | Surf | Adjust | Nominal | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| 1 | TOFF | | | | | | Element 1: lens/lenses group |
| 2 | TFRN | 2 | | 0.000000 | -5.000000 | 5.000000 | Radius Tolerance 1 |
| 3 | TFRN | 3 | | 0.000000 | -5.000000 | 5.000000 | Radius Tolerance 2 |
| 4 | TTHI | 2 | 3 | 2.500000 | -0.150000 | 0.150000 | Thickness Tolerance 1 |
| 5 | TEDX | 2 | 3 | 0.000000 | -0.050000 | 0.050000 | Decenter x |
| 6 | TEDY | 2 | 3 | 0.000000 | -0.050000 | 0.050000 | Decenter y |
| 7 | TTHI | 1 | 3 | 10.000000 | -0.050000 | 0.050000 | Decenter z |
| 8 | TETX | 2 | 3 | 0.000000 | -0.100000 | 0.100000 | Tilt x |
| 9 | TETY | 2 | 3 | 0.000000 | -0.100000 | 0.100000 | Tilt y |
| 10 | TETZ | 2 | 3 | 0.000000 | -0.100000 | 0.100000 | Tilt z |
| 11 | TOFF | | | | | | Element 2: lens/lenses group |
| 12 | TFRN | 4 | | 0.000000 | -5.000000 | 5.000000 | Radius Tolerance 1 |
| 13 | TFRN | 5 | | 0.000000 | -5.000000 | 5.000000 | Radius Tolerance 2 |
| 14 | TTHI | 4 | 5 | 2.500000 | -0.150000 | 0.150000 | Thickness Tolerance 1 |
| 15 | TEDX | 4 | 5 | 0.000000 | -0.050000 | 0.050000 | Decenter x |
| 16 | TEDY | 4 | 5 | 0.000000 | -0.050000 | 0.050000 | Decenter y |
| 17 | TTHI | 3 | 5 | 50.000000 | -0.050000 | 0.050000 | Decenter z |
| 18 | TETX | 4 | 5 | 0.000000 | -0.100000 | 0.100000 | Tilt x |
| 19 | TETY | 4 | 5 | 0.000000 | -0.100000 | 0.100000 | Tilt y |
| 20 | TETZ | 4 | 5 | 0.000000 | -0.100000 | 0.100000 | Tilt z |

*Figure 9: Zemax Tolerance Data Editor*

Some other tolerances, like thickness, decenter and tilt, can be associated with an adjustment surface. As the surfaces in Zemax are defined always through an offset distance of the previous surface, once a thickness tolerance value is added in one lens, for example, all the following surfaces are shifted together by the same distance. This is not what usually happens in real situation, where the increased value in some lens thickness only takes space in some adjacent air surface. This is solved in Zemax with defining an adjustment surface. The adjustment surface compensates variations so that whenever there is an increase in one the surface thickness, the thickness of the adjustment surfaces decreases the same amount. Adjustment surfaces can be also used to compensate decenter and tilt changes.

The surfaces that model an optical system, together with the operands in the tolerance data editor are the necessary data required to run a tolerance analysis.

After the tolerance editor is filled with the appropriate data, the tolerance analysis can be executed. When it is finished, it generates a report file with the data about the analysis. Some of the data used for sorting the elements can be seen of the Figure 10:

```
Criterion            : User defined merit function
Mode                 : Sensitivities
Nominal Criterion    : 0.24054020

Sensitivity Analysis:

                                 |----------- ---- Minimum ----   ----------|
Type                               Value         Criterion          Change
TFRN      2                      -5.00000000     0.41878294       0.17824274
TFRN      3                      -5.00000000     0.08193842      -0.15860178
TTHI      2        3             -0.15000000     0.19466295      -0.04587725
TEDX      2        3             -0.05000000     0.24054020      8.3009E-013
```

*Figure 10: Tolerance Analysis Report File*

In order to calculate which element has greater impact in the optical quality of the system - first, the criterion chosen in the sensitivity analysis is a merit function in which its operands target for desired properties of the system. Then, after running the analysis, the square sum of the tolerances correspondent to each element is calculated. The element with the biggest sum is the one with the biggest impact, and therefore should be assembled first.

Now that it is described the main steps for realizing the sorting algorithm using the Zemax, it is covered on the next session how it was projected and implemented a java program to implement this algorithm in an automated way.

### 4.2.2: The java program

To calculate the assembly order in an automatic way, a java program was projected. The main data flow between the java program and Zemax is illustrated in the Figure 11:

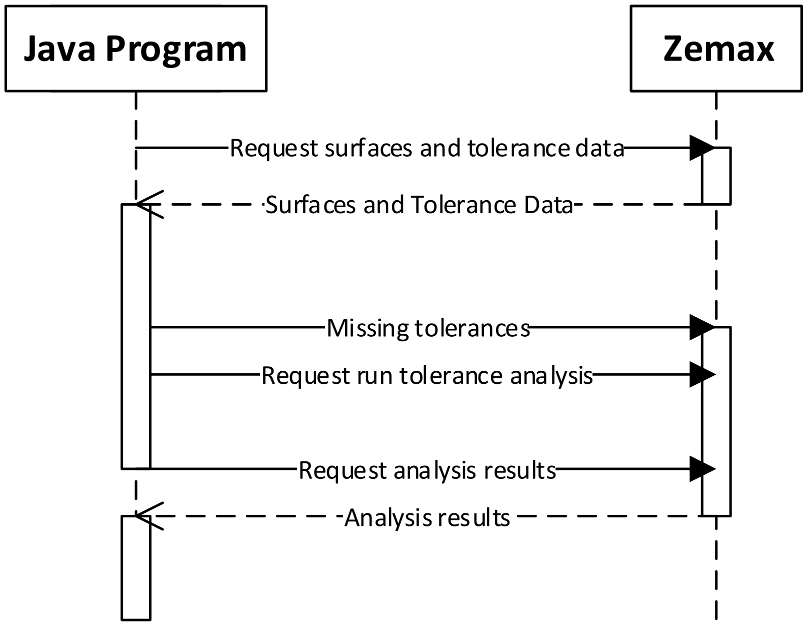


*Figure 11: Sequence diagram showing the main data flow between Zemax and the Java Program*

The program was projected with the following architecture (Figure 12): There are specific classes that are used just to represent and store data, for example about the optical elements and its tolerances. Other classes deal only with the logic part of the program, that involves for example, identifying the optical elements from the data sent from Zemax. Finally, there is a class used as a communication layer between Zemax and the java program. That class encapsulates the communication protocol, so if any changes are made in the protocol, only this class needs to be altered.

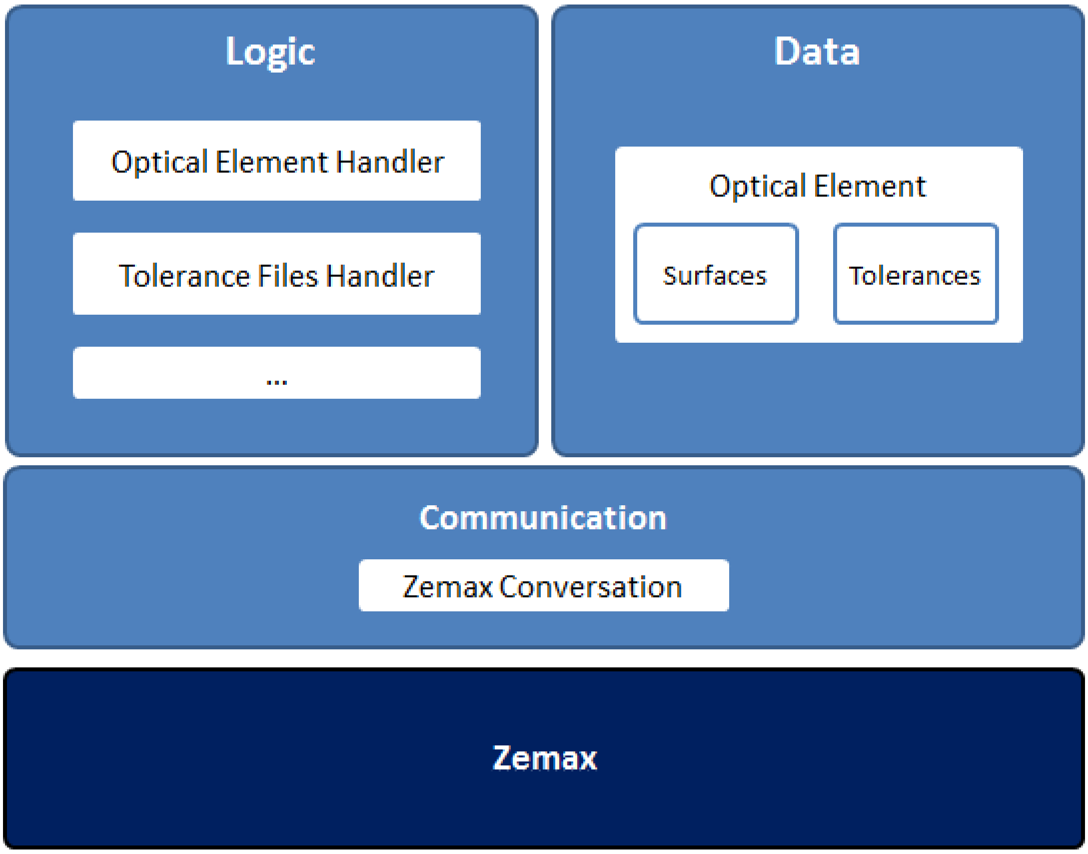


*Figure 12: Architecture of the Java Program*

The operation of the program is – first, it requests all the data present in the Lens data editor and in the tolerance data editor. All the surfaces and tolerances are organized in an entity the form of optical elements, with respective tolerances.

To identify an optical element, the program reads the surfaces on Zemax Lens data editor. Whenever a glass or a group of glass surfaces is present, it stores the data about then and the following air surface in an entity called optical element. The air surface contains data about the elements radius and also is used as default adjustment surface although in real situation, the air surface preceding the element is sometimes chose, or even the only possibility, it was chosen to always consider the following air surface, for reasons of simplicity and limitation the scope of the project, due to limited time. This entity also contains a set of standard tolerances, that are initially created with default values, chosen based on the literature of commercial tolerances (in the case of a lens, they are radius, thickness decenter and tilt, for example). Also, all the optical elements are stored in the java program in an ordered list, and also all the surfaces read from java. The Optical Elements have references that point to the actual surface entities.

Afterwards, the data about the tolerance operands is checked in respect to whether it belongs to any optical element. If the surface that the tolerance operand reference is presented in any optical element, that tolerance is assigned to the optical element, replacing the default values with the prior defined.

Then, the program convert all this tolerance data in a file with specific format that can be loaded by Zemax. After this file is loaded, the tolerance data editor is filled with the necessary data for realizing a tolerance analysis.

After the analysis is finished, the java program reads through the output file and calculate the square sum of the criterion for each element. By construction, all operands in the output file follow a sequence – the operands associated with the first optical element comes first, and so on. Based on that, it is easy to determine which operands belong to each element: the last element operand is always a tilt in the z axis, so the operands that come after a tilt z belong to the next element, and so on. Once each element is associated with a square sum of the changes of its maximum and minimum tolerances, they are organized in form of a list and then sorted so that elements with the higher sums come first in the list.

This concludes the problem of generating an assembly order in an automatic way. The next chapter cover the simulation of an assembly processes and its automation. The whole assembly simulation is used to evaluate this assembly order strategy, comparing to two trivial assembly order where whether the closest the elements are to the laser source, or the measurement planes, the first they are mounted.

# Chapter 5: Assembling Simulation

In order to evaluate the assembly order strategy described on the previous chapter, it is necessary a simulated assembly of the optical system. Also, this can be used in conjunction with a real optical system, in order to implement and automated assembly of an optical system.

It is described in this chapter how it is projected and implemented the automated self-optimized assembly simulation.

## 5.1: Assembling Simulation – Overview

The Figure 13 shows the main steps performed during an assembling simulation. The first three steps are the initialization of the assembly simulation process, and the other characterize a cycle that repeats for each optical element.

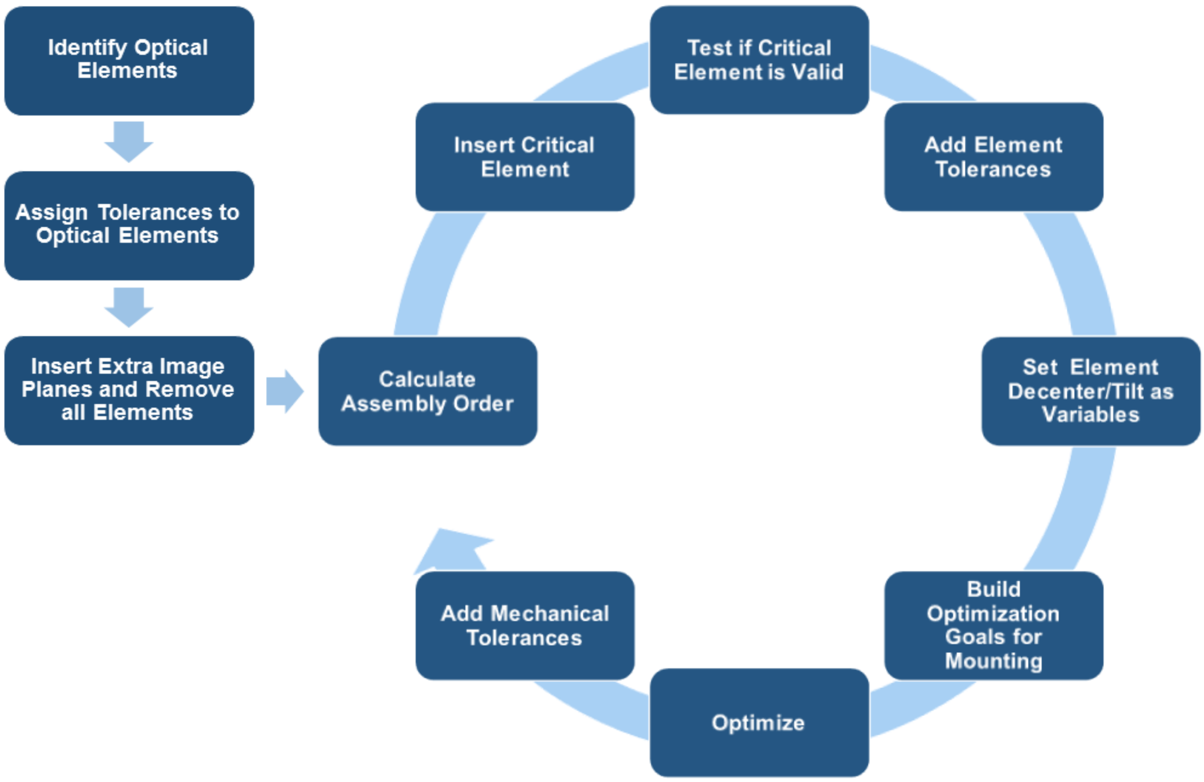


Figure 13: Assembling Simulation

**Identify Optical Elements:**

For the scope of this project, two main kinds of optical elements should be identified: the mirror and the lens. These elements could assume the geometric forms of spherical, plane (in the case of mirrors) and toroidal (in the case of lenses). Also, cemented lenses, compound of two or more lenses, should also be included. Any tolerances related to these elements are identified as well.

**Assign Tolerances to Optical Elements:**

The tolerances used were, as element tolerances the curvature of the elements, in the case of spherical or toroidal components, and the center thickness, in the case of lenses. Mirrors in the ideal case are considered just as a surface, and its thickness is null.

The mechanical tolerances used were decenter in the X axis, decenter in the Y axis, Tilt in the X, Y and Z axis. When the tolerances were not defined prior to the assembly simulation, the default commercial values of the Table 1 were assigned to the elements.

**Insert Extra Image Planes and Remove all Elements:**

This emulates a real measurement system that can measure the beam diameter. To characterize properly the beam, three image planes are necessary as shown in the Figure 14:

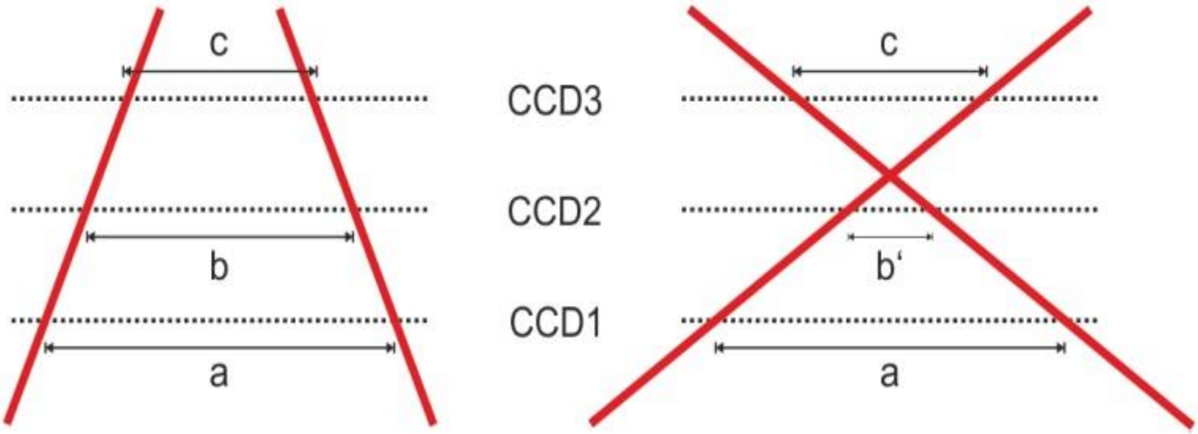


*Figure 14: The pointed lines represent the image planes and the full lines represent the beam outer rays. In order to characterize the beam, at least three measurement image planes are necessary. Measuring the diameter of the beam in the tree planes, it is characterized*

**Calculate Assembly Order:**

Three distinct possibilities are considered here. There are two trivial orders, one of which chose the elements closest to the laser source to be assembled first. Another chooses the elements closest to the image plane to be assembled furt. The third and more complex is the assembly order strategy that is detailed described in the previous chapter. It consists on calculating the assembly choosing the elements with higher impact on the optical quality of the system to be assembled first.

**Insert Critical Element:**

The first element of the assembly order is defined as the critical element, and it is inserted in the system in its initial, previously defined position.

**Test if Critical Element is Valid:**

This tests three conditions:

1. The element is not mounted
2. The entire laser beam passes through the element
3. The entire laser beam passes through the measurement planes

Case the critical element doesn’t satisfy all the conditions, the element is removed and the next element in the list is taken. If no element satisfies the conditions, the assembly process is interrupted.

**Add Element Tolerances:**

In the case of lenses, thickness and radius tolerances are added. In the case of spherical mirrors, a radius tolerance is added. This emulate manufacturing tolerances that occur in the real optical elements

**Set Critical Element Decenter/Tilt as Optimization Variables:**

This key point permit to emulate the degrees of freedom of an assembly system used to position the optical elements.

**Build Optimization Goals for Mounting:**

The goals are taken from a replica of the system which doesn’t contain the elements tolerances. That way, through optimization and alignment of the lens, it is desired to attain the same characteristics of an ideal system, free of tolerances.

**Optimize:**

An optimal minimum in the merit function it is found, and also its respective variable values, which determine the alignment of the critical element

**Add Mechanical Tolerances:**

Decenter and Tilt tolerances are added, representing the positioning error present on real assembly systems, due to for example limited resolution of an assembly robot movement

This Cycle repeats until there are no more elements to be mounted. In the next session it is explained how it was implemented.

## 5.2: Assembly Simulation: Implementation

For implementation of the assembly simulation it was also used the software Zemax for modeling of optical systems, and for the automation of the simulation, it was built a java program which communicates with Zemax through a special protocol. It is the same solution adopted in the previous problem, described in chapter 3, for the same reasons.

The first two steps are the same described on the previous chapter. Then the java program requests Zemax to insert two new surfaces with a pre-defined distance of 50mm apart that was based on a real system measurement planes.

To remove all elements, the java reads all data about the surface materials, and then set all material as empty. This makes all surfaces behave like air surfaces, and emulate the absence of any optical elements. This can be seen in Figure 15.

| | Surf:Type | | Comment | Radius | Thickness | | Material | Coating | Semi-Diameter |
|---|---|---|---|---|---|---|---|---|---|
| 0 | OBJECT | Standard | | Infinity | 2734,570 | | | | 0,000 |
| 1 | | Standard | | Infinity | 10,000 | | | | 1,050 |
| 2 | (aper) | Toroidal | | Infinity | 2,500 | | | | 1,054 |
| 3 | (aper) | Toroidal | | -21,180 | 53,606 | V | | | 1,055 |
| 4 | STOP (aper) | Toroidal | | 21,120 | 2,500 | | | | 1,075 |
| 5 | (aper) | Toroidal | | Infinity | 74,262 | | | | 1,076 |
| 6 | IMAGE | Standard | | Infinity | - | | | | 1,105 |

*Figure 15: Removed Optical Elements in Zemax Lens Data Editor*

The assembly order is then calculated. It is defined before running the program, which order strategy will be used. Three different strategies are used for means of comparison It can be used the trivial, where the elements closest to the source are mounted first. As the elements are stored in an ordered list that already follow this order, this is the simplest option, the list doesn't need to be reordered. The second option is simply reversing the trivial order. A reversed list is easily created from the original list of elements. The third and last option takes the account the elements tolerances and its impact on the optical quality of the system, and it is detailed described in the previous chapter.

Then the critical element is inserted. To do so, information about its material that was previously stored in the java program is simply reloaded in Zemax. To test if the element is valid, three conditions must be satisfied:

1. The element is not mounted:

   This is solved by associating to each optical element a variable that states whether the element is mounted or not. All elements start not mounted, and at the end of a cycle, the value of the variable is changed to indicate that the element is mounted.

2. The entire laser beam passes through the element
3. The entire laser beam passes through the measurement planes

   To test these conditions, it is tested whether the laser beam passes through each element surface. The way to implement that is Zemax is the following.

   Each surface has a parameter called semi diameter. It's half of the surface diameter, and has its name not to be confused by the curvature radius of the lens. This value can be user defined or automatic. When set to automatic, its size is just the necessary for entire laser beam pass through the element.

   The semidiameter value is read and stored. Then set from user defined, which is the default option, to automatic, and the value is read again and compared to the previous one. If the automatic value is bigger, that means the user defined value was not enough to all rays pass through it.

Using this strategy, all the surfaces correspondent to the critical element and to the measurement planes are tested.

If one of the three conditions fail, the element is discarded and the next element of the list is chosen. If all elements fail to satisfy the conditions, the simulation is aborted. A future extension of the program would consider mounting two elements at a time, or even generate new assembly order. As an initial study of these problems reveal them to be of considerably high complexity and time consuming, they are left out the scope of this project.

Then the element tolerances are added - The java program has to each optical element a set of standard tolerances, and for each one, maximum and minimum values. The element tolerances, are generated in a scaled truncated normal distribution by the java program and then are added to the thickness or radius, conform the case, values of the surfaces in the Lens Data Editor in Zemax.

Next, Decenter and Tilts are set as optimization variables**.** In Zemax, decenter and tilt of an optical element is modeled using an auxiliary kind of surface, called coordinate break. This surface has parameter for decenter and tilt in each direction axis of the coordinate system. After a coordinate break the following elements positions and coordinate system are changed. In order to just change one element position and keep the original coordinate system for the subsequent elements, two coordinate breaks and an extra air surface are need. Also, some constraints are added in the air surface and in the second coordinate break so the subsequent elements maintain their position regardless of the values of the parameters in the first coordinate break (Figure 16).

| | | Surf:Type | TCE x 1E-6 | Par 0(unused) | Decenter X | Decenter Y | Tilt About X | Tilt About Y | Tilt About Z | Order | Par |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | OBJECT | Standard | 0,000 | | | | | | | | |
| 1 | | Standard | 0,000 | | | | | | | | |
| 2 | | Coordinate Break | - | | 1,000 | 0,000 | 0,000 | 5,000 | 0,000 | 0 | |
| 3 | (aper) | Toroidal | - | 0 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | |
| 4 | (aper) | Toroidal | 0,000 | 0 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | |
| 5 | | Coordinate Break | - | | -1,000 P | 0,000 P | 0,000 P | -5,000 P | 0,000 P | 1 | |
| 6 | | Standard | 0,000 | | | | | | | | |
| 7 | STOP (aper | Toroidal | - | 0 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | |
| 8 | (aper) | Toroidal | 0,000 | 0 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | |
| 9 | IMAGE | Standard | 0,000 | | | | | | | | |

*Figure 16: Coordinate Breaks in Zemax Lens Data Editor*

The java program inserts the necessary surfaces surrounding the critical element, sets all the necessary constraints and finally set the parameters of the first coordinate break as optimization variables.

Then the optimization goals are built in a way that, after optimization, the system with tolerances behaves as closely as possible to a system with no tolerances at all. In order to create these goals, before the simulation starts, a copy of the optical model file is made, from which these goals can be built.

These goals are expressed in the form of merit function operands, and each operand corresponds to specific rays position in the measurement plane. In this step, the original file is reloaded. All the elements are removed, except the ones already mounted and the critical element. The specific ray positions in specific coordinates in the measurement plane are read and stored. The original file is then reloaded, and these previously read values are used as targets of the merit function used to optimize the system.

Also, some operands that represent boundaries are added to the merit function. This eliminate situation where an optimal point is found, but the optimization variable values make no sense or are not feasible in a real world situation.

With the merit function and optimization variables defined, the java program requests Zemax to realize the optimization. A local minimum in the merit function is found, and the corresponding values of the optimization variables. As the optimization variables are the optical element decenters and tilts, this step emulates the optical element alignment.

As in the real world situation there are always tolerances associated with the inaccuracy or limited resolution of the assembly system, here in the simulation are also added values for these mechanical tolerances. The values are generated following an uniform scaled truncated distribution, between minimum and maximum values defined in the java program.

This completes a cycle that is repeated until there are no more elements to be mounted. Next chapter describes how this assembling simulation was applied to different test systems, and discuss the results attained.

# Chapter 6: Results

This chapter illustrates the tests of the simulation and the results for 5 different test systems. First the systems are presented and then the simulation results for all of them.

The test systems aim for a high level of diversity and follow the model of systems frequently used in the real world. Every system was tested with respect due the trivial assembly order, the reversed assembly order and the assembly order that follow the tolerance based strategy. A Merit Function was used to evaluate the system quality. This Merit function is individual for each test file.

The first system consists of two toroidal lenses opposed to each other. One focus the laser bean and the other collimates it again. A system with such configuration can be used, for example, as a zoom system, when varying the distance between the lenses. It is illustrated in Figure 17**:**

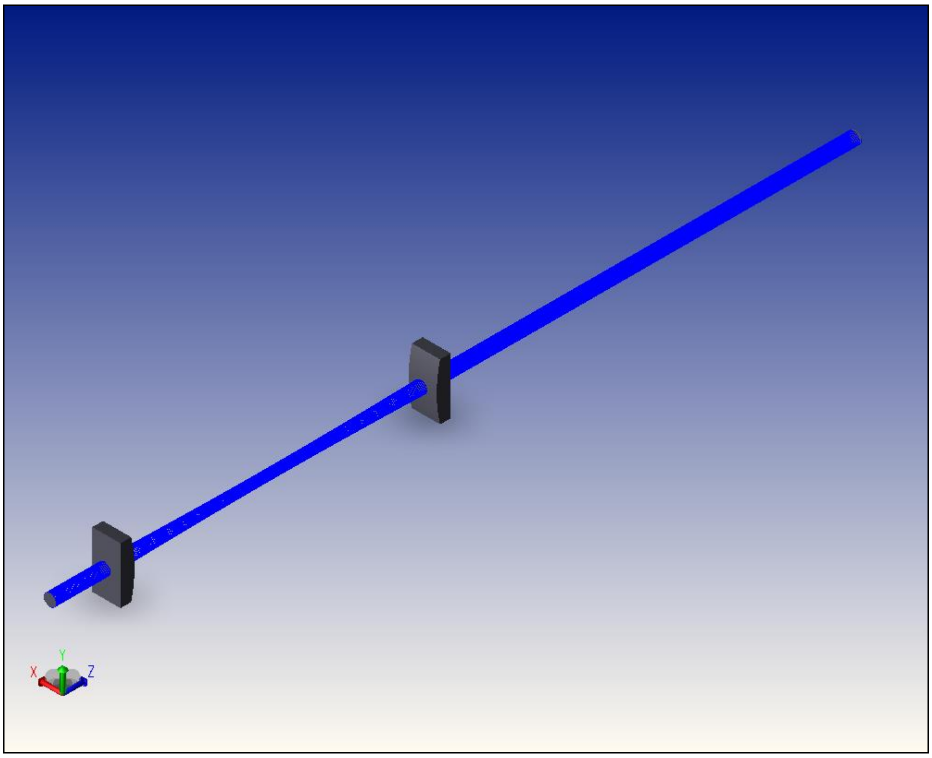


Figure 17: Test System 1

Analyzing this system, an important decision is made. The simulation time for one run, takes approximately 10 min. Even for this simple system, there is a great number of tolerances and an enormous range of combinations. If, for example, it is took each tolerance and instead of using a normal or uniform distribution, and determine that it can assume either its maximum or minimum value, it originates 2^16 different possibilities, as each optical element has six mechanical tolerances, plus thickness and radius. So, using the normal and uniform distribution it is needed an amount of time that is not available to properly evaluate the systems. As the systems grow in number of elements, the number of combinations grows exponentially. So, in order to evaluate the difference between each assembly order and eliminate these variations, It is decided to use always the maximum value tolerances in each optical element. That way, the optical elements are always the same in all simulation runs, and the different assembly order strategy can be really compared in respect due to which one results in the a better system quality. All the subsequent test systems were also tested in the same way.

For the First test system, the attained results are showed in the Table 2. In this case the tolerance based assembling order brings better quality to the system, as expected. Also, it can be noticed that the reverse and the tolerance based order result in the same merit function value. That happens because they are in fact the same order.

| Assembling Order | Merit Function Value |
|---|---|
| Trivial | 0.166 |
| Reverse | 0.146 |
| Tolerance Based | 0.146 |

Table 2: Test system 1 - Results

The second test system is showed in the Figure 18. It is a four lenses system, two of which are toroidal. Theses lenses change the characteristics of the beam in only one direction. A common example of such lens application is the collimation of a fast or slow axis of a laser beam.

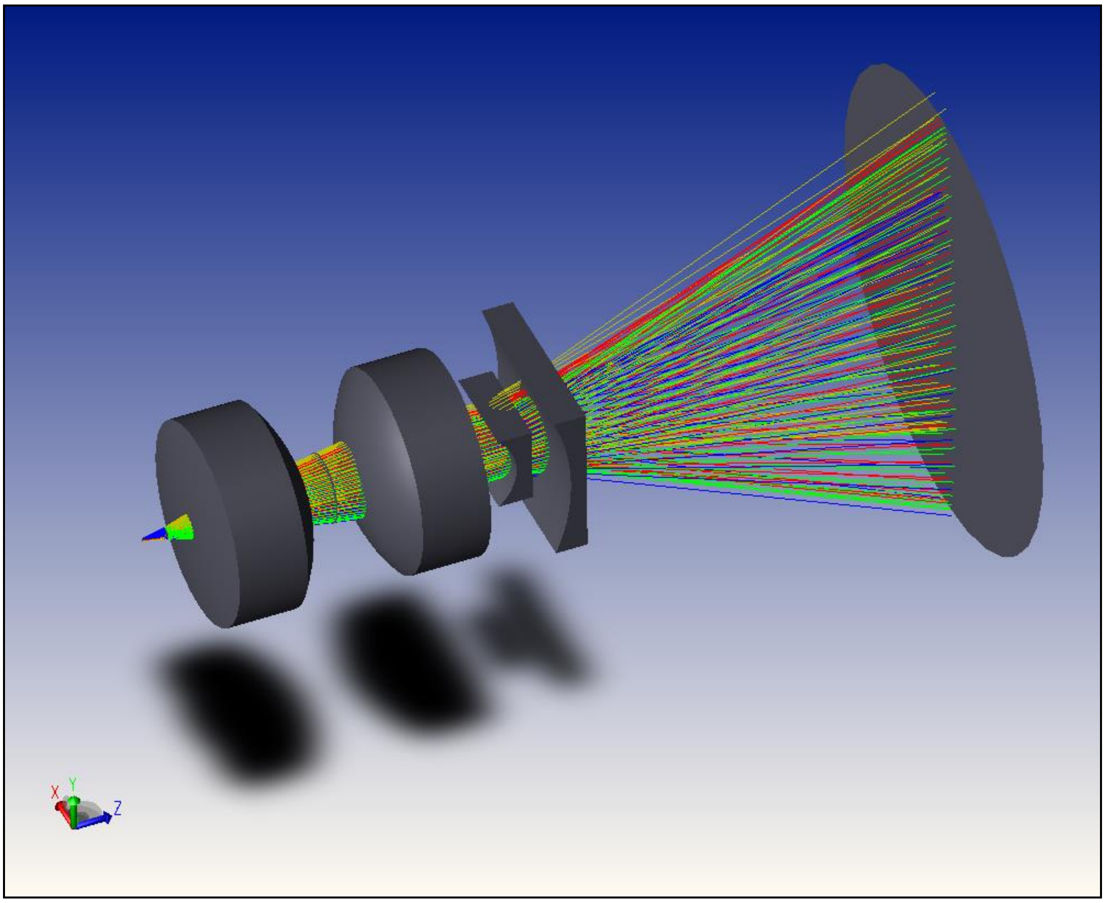


Figure 18: Test system 2

For this system, the results are shown in the Table 3. In this case, the trivial assembly order obtains the best outcome.

| Assembling Order | Merit Function Value |
|---|---|
| Trivial | 0.0543 |
| Reverse | 0.0559 |
| Tolerance Based | 0.0557 |

Table 3: Test System 2 - Results

The third test system is designed to evaluate the assembling simulation in the presence of mirrors. It is composed only of mirrors, and it is illustrated on Figure 19:

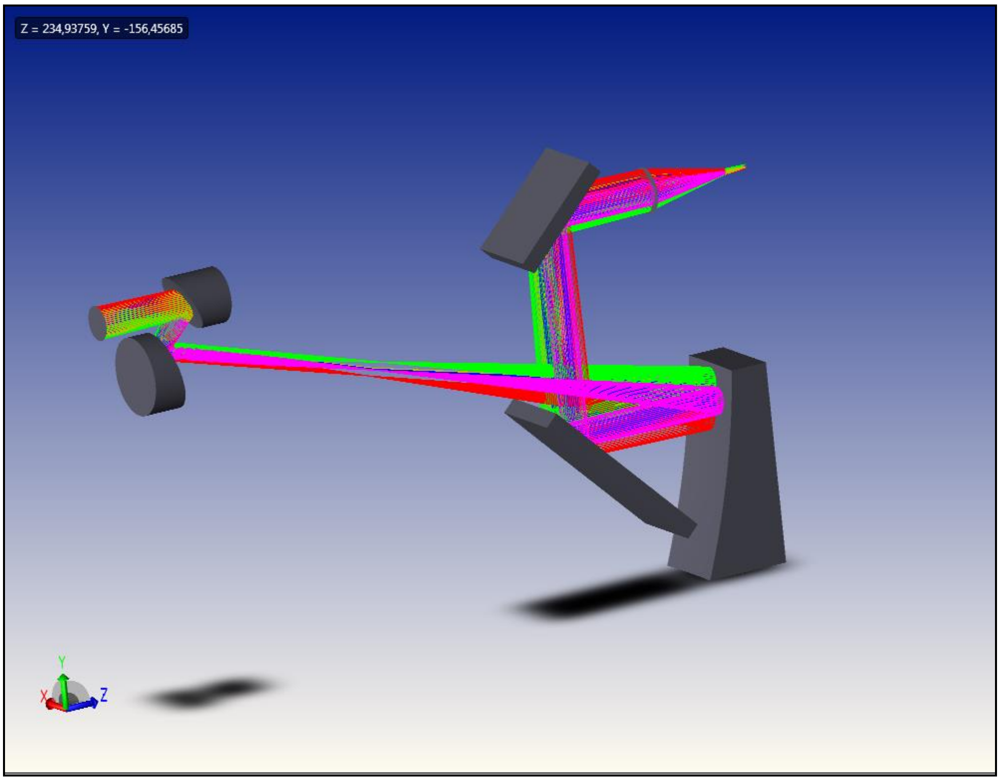


Figure 19: Test system 3

In this case, the results cannot be evaluated for. The reason is that when mounting one mirror at a time, eventually there is some point in the process that the bean cannot reach the measurement planes properly. It can be concluded that some systems are out of the scope of this solution, especially the ones with mirror or strong changes in the direction of the beam.

The fourth test system is composed by both mirrors and glass lenses. A similar configuration can be found in many scanning systems. In the *Figure 20* it can be seen the whole system, and the Figure 21 shows a closer detail of it.

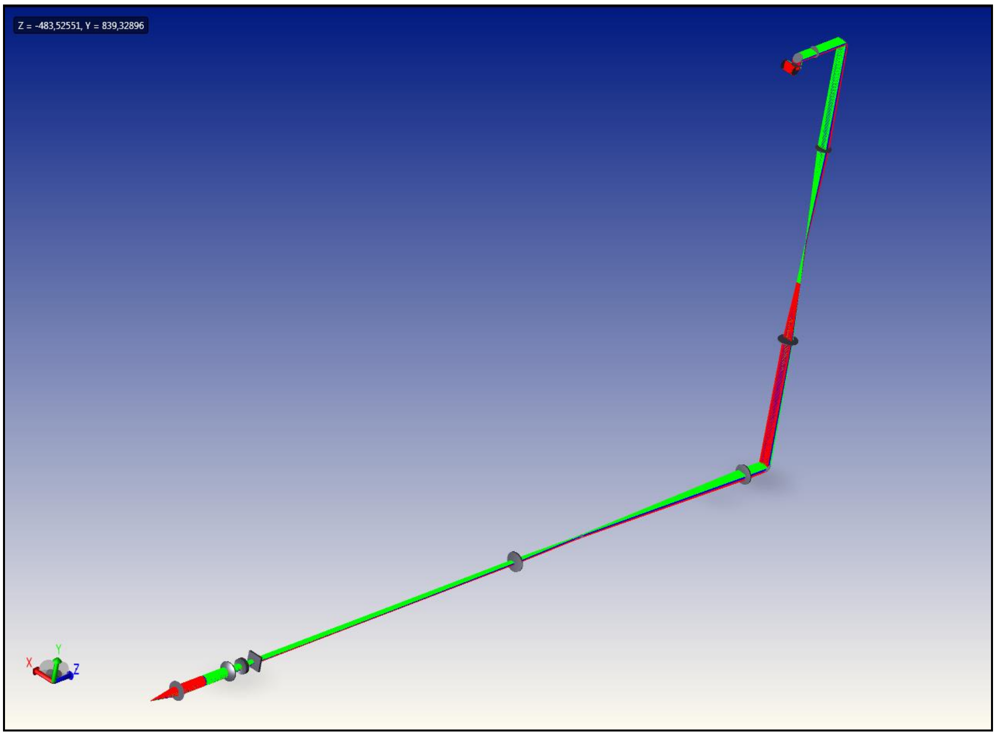


Figure 20: Test system 4

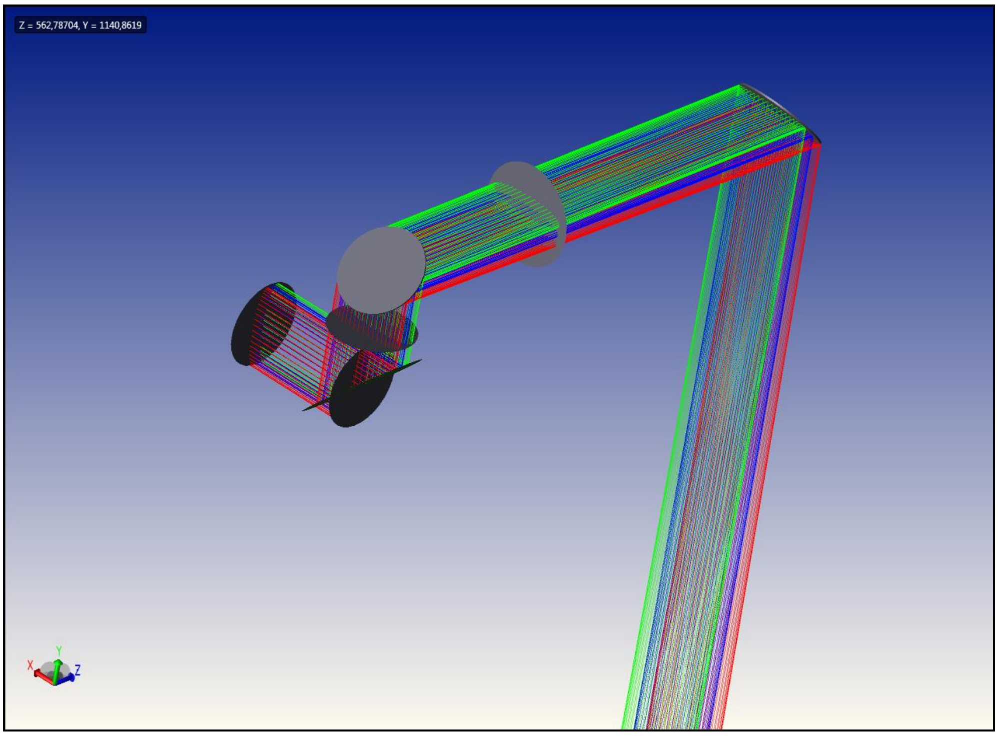


Figure 21: Test system 4 – Detail

At a first try, this system behaves the same way as test system 3. For this case it is proposed a solution. The same system is tested, but the coordinate changes and the mirrors. This can be done because in this system only planar mirror are used, which ideally, and in this model, don’t change any characteristic of the laser beam, besides its direction. The modified system is shown on Figure 22.

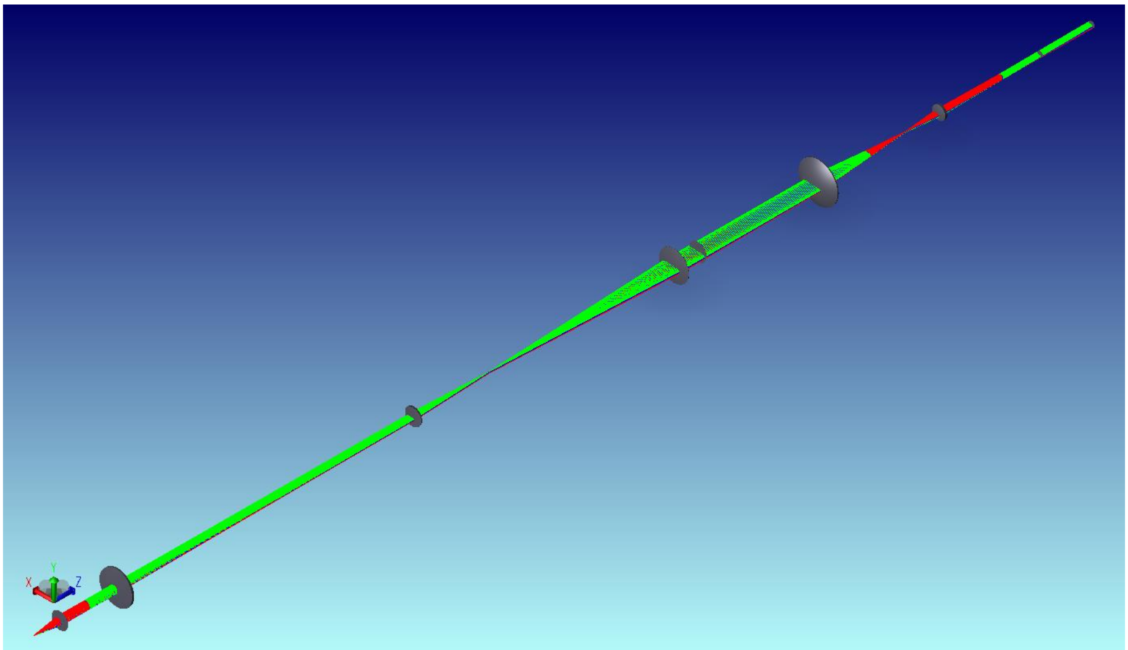

Figure 22: Test System 4 – Modified

The results obtained after this modification are presented in the Table 4. For this system, the reverse assembly order give us the best result.

| Assembling Order | Merit Function Value |
|---|---|
| Trivial | 4.99 |
| Reverse | 4.18 |
| Tolerance Based | 4.97 |

Table 4: Test System 4 - Results

The Fifth and last test system is composed of lenses with a planar base, a geometry that makes it easier for automated assembly than the traditional rotational symmetric lenses. It is shown in Figure 23.

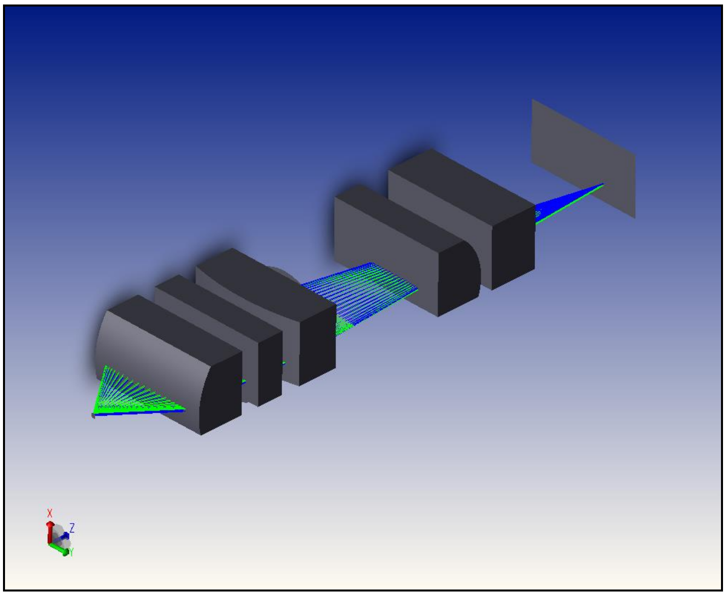

Figure 23: Test system 5

The results for this system are showed in the Table 5. The results for this system also correspond to the prior hypothesis that the tolerance based assembling order provides better results.

The assembling with reversed order cannot be performed. As it can be observed in the Figure 23, the initial laser beam covers a large field angle. This causes the conditions that test whether the critical element is valid in the assembly simulation process to fail, interrupting the simulation. It is important to notice, that if these condition fails, the goals for the merit function cannot be created, and therefore the optical elements cannot be properly aligned.

| Assembling Order | Merit Function Value |
|---|---|
| Trivial | 0.08 |
| Reverse | - |
| Tolerance Based | 0.06 |

Table 5: Test System 5 – Results

# Chapter 7: Conclusion and Perspectives

This project is a step towards building an automated self-optimized assembly system. This kind of system is needed in high wage countries to compete against the low wage countries pressure for market competitiveness and it is advantageous even for a more flexible and low production situation.

The first part of this project deals with the problem of choosing an assembling order. It was proposed an assembling order strategy based on the optical elements tolerances, and the initial hypothesis that the alignment of the optical elements can better compensate the imperfections caused by the tolerances if this order is chosen. This is implemented using an optical model software in conjunction with a java program, making possible to automatically calculate the assembling order given an optical input system.

The second part of this project is the project and implementation of an automated assembly simulation. This simulation is used to evaluate the assembling order strategy developed in the first part. It was also implemented using the optical model software together with a java program.

Analyzing the whole set of systems, we can conclude that not always the tolerance based assembling order brings the best quality for the final system. Some systems cannot compensate the element and mechanical tolerances by simply alignment of its optical components following this order.

Another important observation is that the solution developed in this project can be extended in order to incorporate a bigger variety of optical systems in its scope. Systems which don’t satisfy the conditions that test if the critical element in the assembly simulation is valid might be assembled, if the solution here implemented extends to generate more assembly orders that consider mounting two optical elements at the same time.

After the end states of the project it is also noticed that the testing procedure to decide whether an optical element is suit to be mounted or not. The test Check the conditions for one element and, case they are satisfied, the element is mounted. For some systems, a problem might occur – the choice of assemblying a given element in a step might result to the not fulfilment of the conditions element mounted after this one. To do a more abroad and robust test, the whole mounting sequence should be contemplated in each individual cycle of iteration, that is, to prevent that a mounting of a given element would lead the whole system to a “dead end” situation where one of its elements fail in the test conditions.

Also, when implementing the system in real situation, extra tolerances can be added to  the model if they are considered relevant and significantly affect the quality of the optical system. Finally, the next step towards the realization of a self-optimized optical system is the integration of the simulation with a real robot cell.

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