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DESIGN METHODOLOGY FOR RECONFIGURABLE PRECISION SYSTEMS APPLIED TO AN ULTRAPRECISION LATHE

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Abstract. *In Brazil, researches in the field of precision engineering oblige designers to find simplified solutions to obtain quality and efficient systems with low financial resources. In order to support designers in this challenge, it was developed a design methodology that allows achieving the required quality results from a simple systematic approach. Such approach consists in the use of quality parts and components from unused precision equipments. Thus, each part becomes a module that can be combined with other modules to compose a new system, with new function requirements. To do this, it's necessary to know all the characteristics of the module and its interfaces. After extracting this information, a module library is created. This methodology permits the design of reconfigurable systems, by changing of particular modules from the system to adapt it to new functions. The methodology is applied in the design of an ultraprecision lathe to produce conical metallic mirrors.*

Keywords*: Reconfigurable systems, Design methodology, Precision engineering, Ultraprecision lathe.*

1. Introduction

The precision engineering is a field with low exploration in Brazil due to lack of financial support to conduct researches in this area. The greatest challenge to the researchers is to obtain satisfactory quality results with low financial support. Generally, precision mechanics systems are developed to attempt a small range of application, having low possibilities to be used in other tasks which need components with higher quality. Thereby, in some cases, the equipment stays unused or looses their functions in a productive chain or in a deactivated research area. The idea of this paper is to present a design methodology based on reconfigurable systems, developed to help designers to conduct designs in the field of precision engineering, being able to use components or systems from used precision equipments as part of a new conception design.

2. The design methodology

2.1. Reconfigurable precision mechanical systems

The design and operation of precision mechanical systems are only possible after dominating the principles of precision engineering. Some authors described these principles, like Weck (1992); Slocum (1992); Teague (1998); Schellekens (1998); Hale (1999); e Nakazawa (1994). Pereira (2004) had compiled all these information to create support reference texts for precision engineering designers.

In a generic way, precision engineering systems have much more complexity and needed aids, compared to conventional systems. The costs involved in designs with high quality requirements are also higher in this comparison.

Another important fact to be considered, not only in Brazil, is the existence of unused high quality equipments with components which are suitable to be used in new configurations. If the equipment is not more useful in the actual configuration, its high quality parts may be worth to compose other equipment, with different functions. This procedure is explored by Pereira (2004), who nominate it 'reconfigurable precision mechanical system'. By using a set of components organized as modules, it's possible to compose different kinds of systems, to achieve different functional specifications, and guaranteeing the required final quality to the system and respecting the related design principles.

This kind of design procedure aloud a significant cost reduction in the acquisition of components, but demands additional human work on the eventual maintenance of the components or modules and the determination of the characteristics of its interfaces. Most of these modules had not been designed to be part of a modular system and their interfaces must be prepared to do so.

Before presenting a design methodology, the first step during design of a modular system is to make a correct system function decomposition to define the modules. After that, it's necessary to characterize the modules, making possible to predict their behavior after the system composition. Then, it's necessary to present the main resources to conduct the design methodology.

2.2. System decomposition

The proposed design methodology is based on modular systems. To achieve modularity in a system it's necessary to decompose the global system into basic functional elements, mapping these elements as basic physical components, and then integrating these basic components as a modular system able to attend the desired functions. During the decomposition, one must concern about the level of details to be achieved. Low details mean low modularity. High level of details means high complexity.

The most used tool to accomplish system decomposition is the functional decomposition. The first step consists in formulate the system global function, which must be clearly defined to represent the required system main function. This global function is then decomposed into sub-functions with independent sub-systems to be developed individually.

Precision mechanical systems generally have their global function related to carry out a technical task on a component or a sample. These technical tasks are: measurements, material removal, laboratory tests, changing of materials characteristics, etc. These generic tasks give us an idea of which components are necessary to compose the technical system. These components or modules are: Relative movement modules; Structure modules; and Complementary functions modules.

Relative movement modules are linear stages, spindles, rotary tables, tilt tables, XY tables, and parallel robots. Structure modules are machine tool beds, tool holders, and auxiliary structure components. Complementary modules are related to the machine tool main control, movements control, environment control, independent measuring systems, coolant management, and chip removal.

Precision mechanical systems are generally composed by combination of these three kinds of modules. Depending on the complexity required to the system, the number of needed modules varies a lot.

2.3. Modules and interfaces characterization

The final quality of a system depends on the errors composition from each component integrated in the system. If we know the components relevant errors of a required class of uncertainty, it's possible to predict the accuracy level that the assembled system can reach. In other words, it's possible to know if the quality function required for a certain system can be achieved by the use of existing modules. This information is obtained during the conceptual design. To assure this conclusion, it's necessary to know the characteristics from each module that will compose the new system. It's also important to know the interfaces conditions, preventing from possible changing of behavior when different modules are assembled. The correct characterization of the modules must consider all the design principles about precision engineering and provide information about static and dynamic behavior, kinematics, geometrical conditions, thermal behavior, control conditions and all other important details that describe the module and its interface.

To obtain this characterization, a set of questionnaires extracts the relevant information from each important parameter from the modules. These questionnaires were developed and presented by Pereira (2004). The questionnaires can be applied to extract information from the three kinds of modules listed. As an example, the questionnaire to get information about the module static behavior is shown in Table 1. After extracting all the information from each module, it's necessary to condensate and groups this information to permit an easy access.

Table 1: Questionnaire example

Static behavior	
1 - Which is the module weight?	2 - Which is the module load capacity?
3 - Other modules weights interfere in this module function execution?	4 - Is there a defined interface in this module that allows assembly with other modules?
5 - Which kind of constrains exist in the module interface to allow a correct assembly?	6 - Is there any degree of freedom in the assembly between modules?
7 - How many assembly interfaces exist on the module?	8 - Does the module permit only one fixture position during assembly?
9 - Is there any repositioning assurance in reassembly between modules?	10 - Does the fixture generate residual stress that commits the module function execution?
11 - Has the module enough stiffness to be part of the structural force circuit in the system?	12 - Has the module structural stability?

2.4. Modules library

The best way to condensate all the extracted information from the modules is to create a modules library. This library must have this information, complemented by a CAD model to permit virtual assembly for each system composition. After the insertion of all known and available modules, some complementary modules can be added to the library from the market. It permits a quick composition for new reconfigurable system, allowing cost estimation.
In general, manufacturers give details about components and systems. It can be used as a start point to help in selection. But designers must be aware from trusting in all given information. To assure the components performance, certified tests must be done. Figure 1 shows an example of module a in the library.

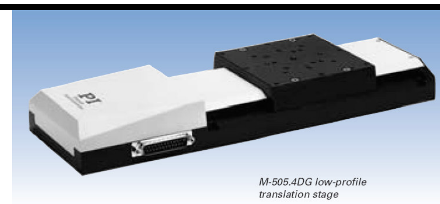
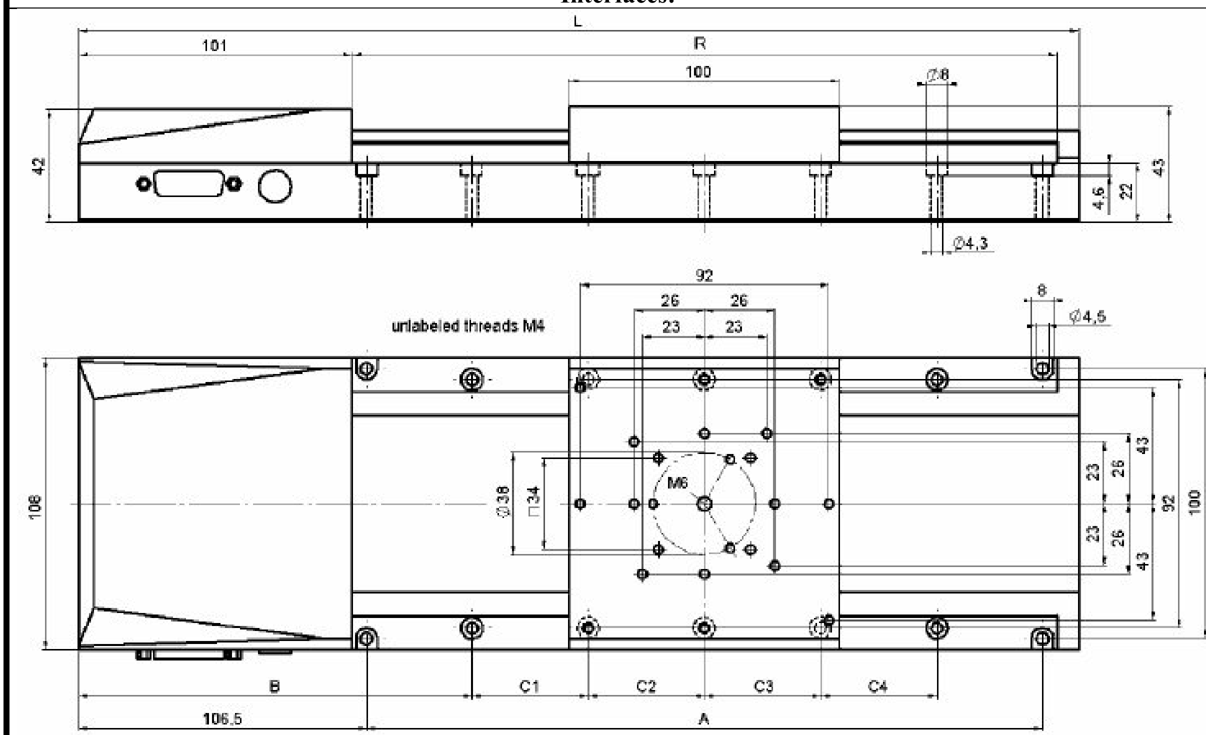
LINEAR STAGE PI M-521.DD N°: **006** Type: Relative movement module Manufacturer: Physik Instrumente Location: Materials laboratory Description: Rolling guide way with CC motor drive, directly assembled to the fuse, and with high quality of movements and positioning, integrated to its own movement control hardware and software.	
Static characteristics: Weight : 6,1 Kg; Normal load capacity : 1000 N; Maximum lateral force : 200 N; Maximum pull/push force in movement direction: 80 N;	**Dynamic characteristics:** Smooth movement, without Stick / Slip; There is no significant vibration generation in the drive;
Kinematics characteristics: Travel range : 204 mm; Velocity to 50 mm/s; Ball screw pitch: 2 mm/rev;	**Geometric characteristics:** Minimal incremental motion : 0,1 µm; Bidirectional repeatability: 0,2 µm; Origin repeatability : 1 µm; Straightness / Flatness: 1 µm / 100 mm;
Thermal characteristics: There is heat generation in the drive motor, but the system assembly avoid enough propagation to interfere in the system geometrical behavior ;	**Control characteristics:** CC driver with movement control hardware and software, needing a computer; Nominal motor power : 30W; Nominal voltage range from 0 to 24 V DC;
Interfaces:	
	
- The module geometrical interfaces are shown in the scheme above :	
Observation:	
The module is assembled in the sclerometer, located in Materials Laboratory ;	

Figure 1. Example of component in the modules library

2.5. Design methodology for reconfigurable precision mechanical systems

In Figure 2, the complete scheme of the proposed design methodology is shown. The process is divided in seven steps. Each step has a main task to be executed and must generate a complete documented response to permit advancing to next step. Each step has a set of activities during detailing the process. All the process is supported by a data bank were the listed documents and tools are available. The key to success here is making a detailed documentation in each step. The right documentation in one step simplify the next one, making the methodology more efficient.

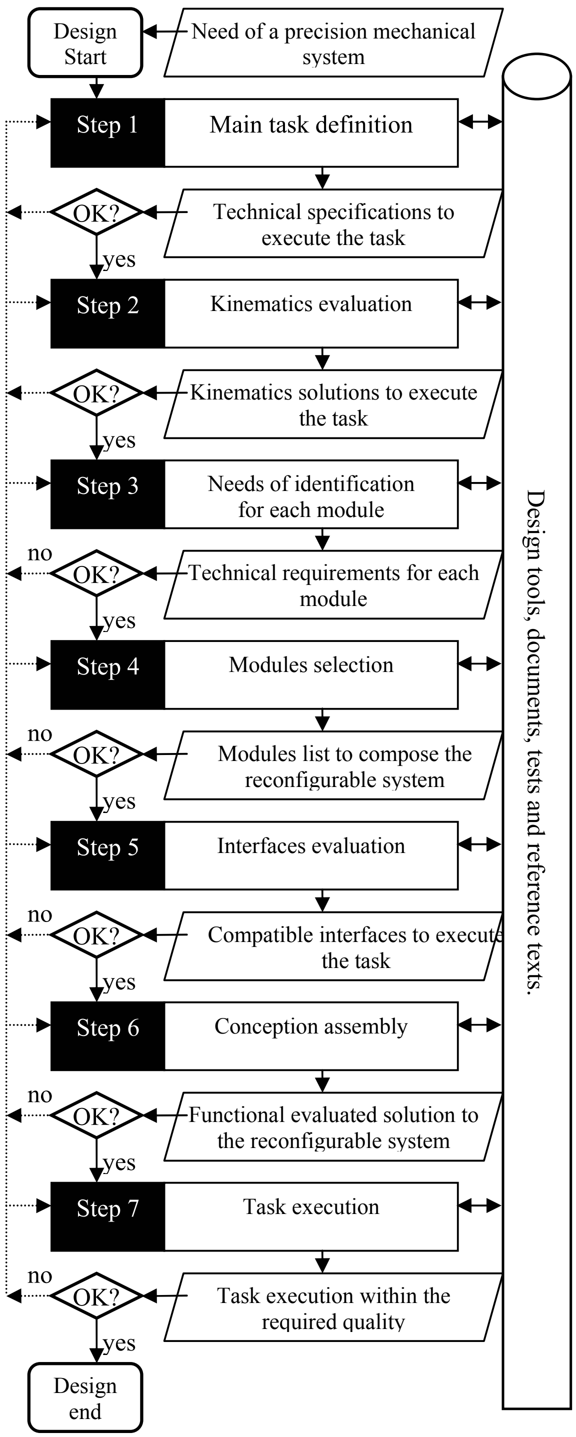


Figure 2: General scheme to the design methodology

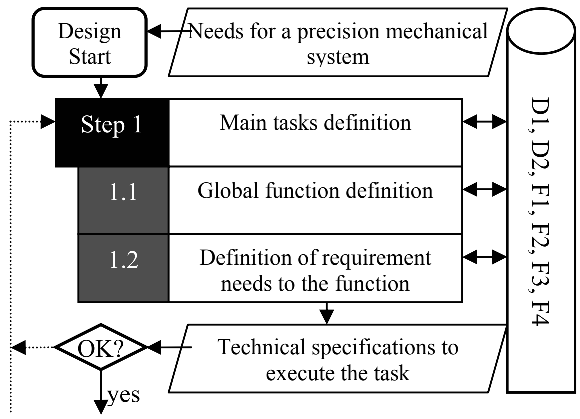


Figure 3: First step in the design methodology

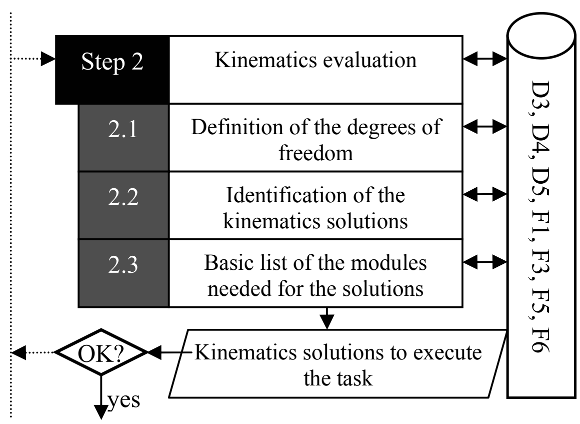


Figure 4: Second step in the design methodology

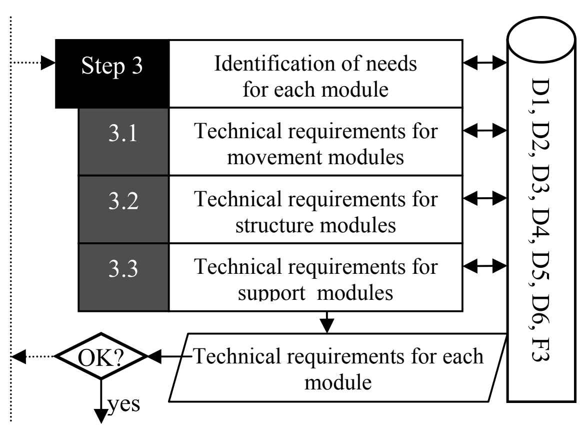


Figure 5: Third step in the design methodology

All designs must start from an initial need. The first and essential action then consists in well define the task to be executed from the designed system. In Figure 3, the methodology Step 1 is detailed. This step consists in performing two activities. Activity 1.1 is related to the system global function definition, followed by 1.2, the definition of all needed requirements that the system must have to execute the task. These two activities must be documented with details (D1 and D2). Some design tools applicable to these activities are the functional decomposition (F1), specific questionnaires and tables (F2 and F4), and the commented design principles (F3).

Figure 4 shows the Step 2, responsible for the kinematics evaluation of the system. Is this step there will be evaluated all the possible kinematics solutions to execute the main task. In the activity 2.1, the needed degrees of freedom to compose the system must be identified (D3). From the degrees of freedom, in activity 2.2, it's possible to take conclusions about the possible system kinematics solutions (D4). In the activity 2.3, based on the design principles for precision engineering (F3), it's possible to decompose each found solutions in terms of the three basic types of modules (D5) shown before. This modules list isn't yet the final modules list to compose the system, but gives a close idea about the kind of components necessary to assembly the system.

In Figure 5, Step 3 is detailed. Its objective is clarifying all the needs to each related module. These needs must be listed as technical requirements, always based on the design principles for precision engineering. The activity 3.1 is focused in extracting technical requirements for relative movement modules, making the right documentation of it (D6). In the same way, Activity 3.2 is responsible for structure modules and Activity 3.3 for complementary functions modules. This work must converge to the task specifications (D2), extracted during Step 1. Moreover, all the expected modules errors compositions must stay in agreement with the specifications obtained in Step 1, to assure the system final accuracy.

Until now, all the design process was conducted in a conceptual form. Following the first three Steps, the designer learns with rich details about what is necessary to reach the final and desired quality to the system.

In Step 4, showed in Figure 6, it's time to consult all the available resources, carrying out the modules selection to compose the system.

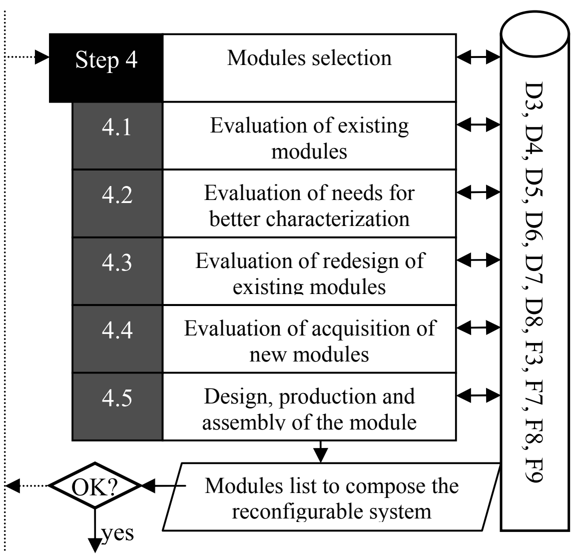


Figure 6: Fourth step in the design methodology

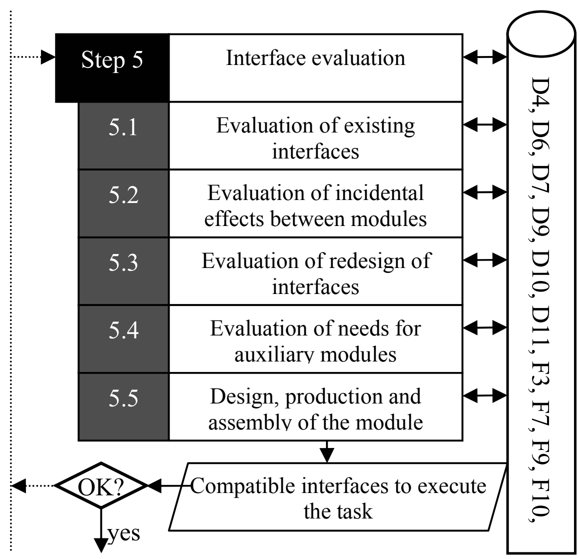


Figure 7: Fifth step in the design methodology

In Activity 4.1, the designer is responsible for evaluating the modules list, comparing all the listed needs (D6) to the available modules characteristics. In some cases, the extracted characteristics form modules in the library are not enough to permit its evaluation to compose or not the required systems, and then a new and more detailed characterization becomes necessary, made in Activity 4.2. If some module has almost all needed characteristics required, in Activity 4.3, the designer can evaluate the possibility of redesigning the module to adapt it to new requirements. It might be cheaper than buying a new module, as predicted in Activity 4.4.

If the designer could not select all modules after realizing all these activities, the final solution, suggested by Activity 4.5, is to design, produce, assembly and characterize a new module to satisfy the need. In the final of the Step 4, the designer must have a complete modules list to compose the reconfigurable system, in agreement with all the related quality specifications to assure the system final quality. In this step, reconfigurable systems are also structured. All modules needed for reconfiguration are also selected and listed. All the chosen conceptions must be predicted.

After having the modules lists, it's necessary to evaluate interfaces conditions in Step 5, shown in Figure 7.

Activity 5.1 relates to evaluation of interfaces compatibility, followed by the investigation about existence of incidental effects between modules in Activity 5.2. These incidental effects are thermal sources, vibration, residual stress, etc. These two evaluations are made based on a design tool developed to this purpose, the interfaces evaluation matrix, shown in Figure 8.

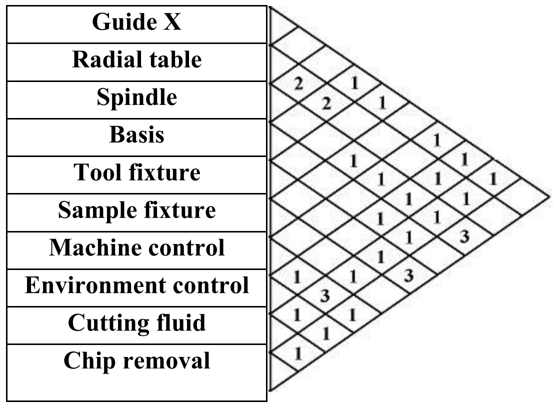


Figure 8: Interfaces evaluation matrix

In this matrix, each module is compared to the others. If there is some relation between them, this relation is then marked in the matrix following the notation:
1 – Modules are perfectly compatible;
2 – Modules are not geometrically compatible;
3 – Modules are compatible, but incidental effects exist;
4 – Modules are not geometrically compatible and incidental effects exist;

Through this matrix, it’s possible to identify all the actions needed to assure an ideal system assembly, working each interface to guarantee the final system quality. A requirements list for interfaces must be generated (D10), followed by a list with all the actions and problems related to each interface (D11). Activities 5.3, 5.4 and 5.5 are responsible for solution all these problems. In Activity 5.3, a redesign of existing interfaces is suggested. In activity 5.4, auxiliary modules can be suggested to assure interfaces compatibility.

In Activity 5.5, auxiliary modules are designed, manufactured, assembled and characterized to compose the system. Solved all the interfaces problems, the next action is Step 6, showed in Figure 9, where the system will be assembled.

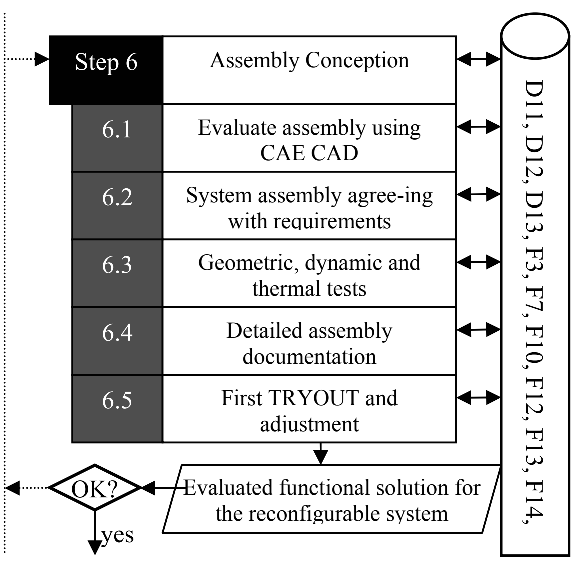


Figure 9: Sixth step in the design methodology

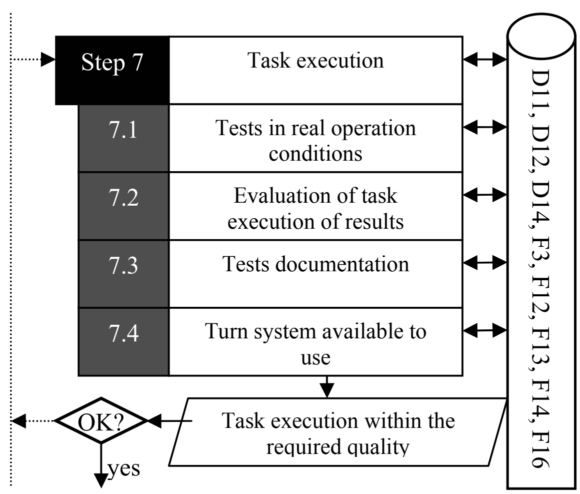


Figure 10: Seventh step in the design methodology

The first action in this step consists in a virtual assembly (Activity 6.1, D12), followed by computerized simulations. After concluding the virtual model, the system can be assembled (Activity 6.2). Depending on the available resources, geometric, dynamic and thermal tests (Activity 6.3) can be done to confirm the system predicted behavior. All the assembly process must be documented to help in maintenance and in future similar systems solutions (activity 6.4, D12). At least, an initial tryout (Activity 6.5, D13) is conducted to test the functionality and to check for needed adjustments.

Step 7, in Figure 10, is shown the final methodology action, and consists in executing the task to which the system was designed. Activity 7.1 relates the system operation in real conditions to evaluate the system response and propose fine adjustment (Activity 7.2). All this procedure must be documented (Activity 7.3, D14) to be used as a "road book" for the system. After checking all details and being sure about the quality results given by the system, it can finally became available for continuous use (Activity 7.4), which finishes the design methodology.

3. Development of an ultraprecision lathe to produce conical metallic mirrors

Conical mirrors are needed in laser interferometers researches conducted by the Metrology Laboratory at UFSC. Each new interferometer developed needs a different mirror concept, which makes difficult the acquisition by buying new special manufactured mirrors from the international market. It is also prohibitive the cost involved in the acquisition of a dedicated machine to produce these mirrors. In a way to solve this demand, a reconfigurable machine was developed to produce the required mirrors.

Following the shown design methodology steps, step 1 is finished with the technical specifications to produce the conical metallic mirrors in Table 2. Step 2 resulted in two possible solutions to the machine, as shown in Figure 11.

Table 2. Mirrors specifications

Specifications for conical metallic mirrors	
Diameter	20 to 100 mm
Width	0,5 to 50 mm
Conical angle	0 to 45º with 1' maximum error
Maximum form deviation	3 µm
R_a	Lower then 30 nm
Material	Filtered aluminum
Quantity	2 to 10 mirrors in each order

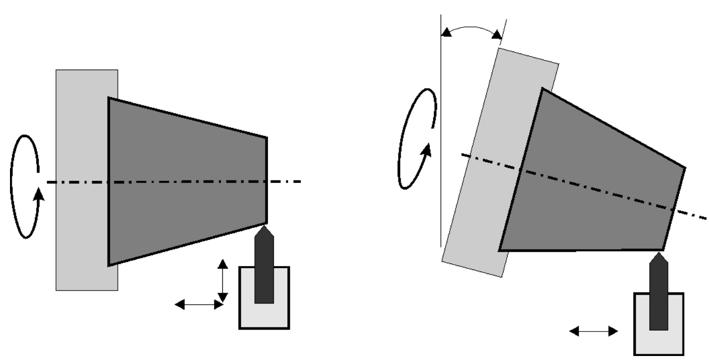


Figure 11. Kinematics solutions to produce conical surfaces

These two kinematics solutions have individual modules and requirements lists to assure the ultraprecision lathe final quality. Table 3 shows the modules and requirements list to the chosen kinematics solution.

The next step (step 4) is finding allowable modules from the modules library to assembly the machine. In this case, some needed modules had more than one option in the library. To choose the appropriate one, quantitative and qualitative comparisons were done.

In step 5, interfaces were evaluated, as shown in Figure 8. Based on the evaluation matrix, some actions needed to be performed to assure quality in the final assembly. In step 6, a virtual assembly was done, followed by the real system assembly, as can be seen in Figure 12 and Figure 13. At least, Figure 14 shows machined conical metallic mirrors.

4. Conclusions

The methodology is flexible and easy to be followed. The key to success is making a detailed documentation for all steps, being sure about all the collected information reliability to permit correct predictions about the final system accuracy. An advantage of this methodology is the possibility to compose systems from used equipment. Through this approach, design can become simpler and cheaper.

Table 3. Modules requirements to the machine

Module	Requirements
Guide X	Min travel of 100 mm; Max straightness error of 1,5 µm; Integrated drive motors with low vibration and heat generation; Min load capacity of 200 N; Travel speed from 0 to 500 mm/min;
Radial table	Load capacity enough to support the linear guide or the spindle; Uncertanty in angular positioning in the order of 10”; Enough stiffness to compose the machine structure circuit;
Spindle	Aerostatic bearing; Min Load capacity of 100 N; Max axial and radial runout of 0,5 µm; Rotation speed from 1000 to 3000 rpm; Integrated drive motor with low vibration and heat generation;
Basis	Passive isolation of internal and external vibration;.
Tool fixture	Tool high adjustment with sensibility of 0,1 mm; Min stiffness of 40 N/µm; Low weight, but with robust construction; Standard diamond fixture system;
Work piece fixture	Work piece fixture concentricity in the order of 0,05 mm; Ability to fixture work pieces from 20 to 100 mm diameter; Balancing facilities system integrated; low inertial moment; Avoid residual stress during fixture;
Machine control	Smooth movements generation from 0 to 500 mm/min; Spindle rotation control;
Environment control	Temperature control in the order of 20 ± 1º C; Avoid heat and vibration sources near the machine; Class 1000 clean room;
Cutting fluid	Cutting fluid flow until 100 ml/min and 3 bar air pressure; Avoid vibration and sound generation to not disturb the machining process; easy positioning for the injection point;
Chip removal	Conventional chip removal vacuum pressure; Avoid vibration and sound generation to not disturb the machining process;

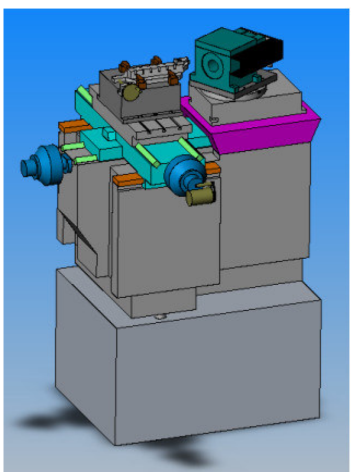


Figure 12. Virtual assembly

Figure 13. Final assembly

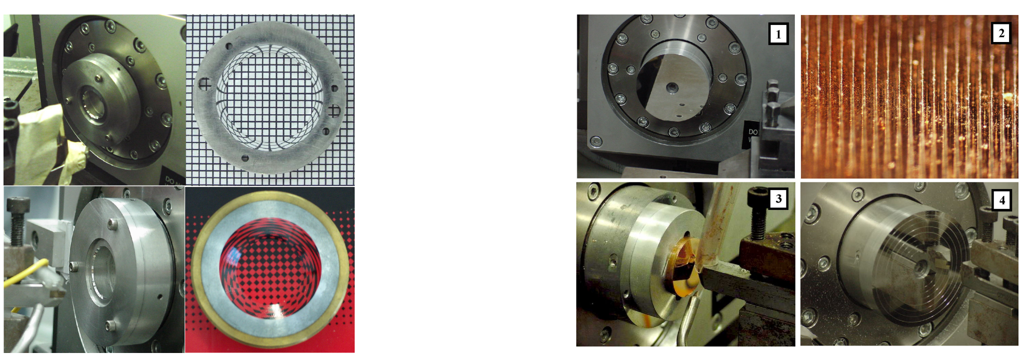


Figure 14. Machined conical metallic mirrors and other examples

5. References

Weck, M. Werkzeugmaschinen Fertigungssysteme, vol. 4. VDI-Verlag, 1992.

Slocum, A. 1992, Precision Machine Design, Prentice Hall, New Jersey, 1992.

Teague, E. C. Donmez, A. M. Basic Concepts for Precision Instrument Design: Designing Instruments and Machines to Have a High Degree of Repeatability. NIST. Tutorial for ASPE. St. Louis, Missouri, October, 1998.

Schellekens, P. et al. Design for Precision: Current Status and Trends. Annals of the CIRP vol. 47/2/1998 pp 557-586.

Hale, L. C. Principles and Techniques for Design Precision Machines. Ph. D. Thesis, Lawrence Livermore National Laboratory, University of California, February 1999.

Nakazawa H. Principles of Precison Engineering. Oxford University Press, 1994. ISBN 0 19 856266 7.

Pereira, M. Metodologia de Projeto para Sistemas Mecânicos de Precisão Reconfiguráveis. Tese de doutorado. EMC – UFSC. Florianópolis, 2004.

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