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PRELIMINARY DESIGN OF AN ATTITUDE SIMULATOR BASED ON A THREE DEGREES OF FREEDOM AIR BEARING

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Abstract. *This work presents part of a development program for a three degrees of freedom attitude control simulator using air bearing. The definition of the system architecture, preliminary sizing of components, design and manufacture of the air bearing are addressed in the text.*
The purpose of the simulator is to serve as a platform for assessing the performance of attitude control systems for satellite applications. The system should be able to simulate orientation changes as large as possible minimizing the effect of external torques.
The main components of the system are: power supply, three momentum wheels, attitude measuring system (gyroscopes) and a mechanical system for the fine tuning of the center of mass position. The reaction wheels are actuators that apply the torques to control the attitude of the system tracking the required orientation. The power supply system is a set of batteries that provides energy to all electrical components: the attitude measuring system, momentum wheels motors, and digital control cards. The attitude measuring system may be either a pair of DTG gyros; this system is responsible for providing an accurate estimate of the attitude of the system. Finally, mechanical system for the fine tuning of the center of mass position is necessary for the three-dimensional balancing of the simulator such that gravitational torques are compensated.
The simulator is formed by two acrylic hemispheres of 350 mm in diameter. Acrylic was chosen to minimize the structural mass of the system and provide electromagnetic transparency; as a consequence, the system may be controlled by a remote computer. The hemispherical air bearing was manufactured in aluminum according to the methodology described as follows. Initially, the following tasks were performed: preliminary sizing of components based on geometric modeling, mass distribution estimate, and CAM programming; the software Unigraphics NX4 was used as tool for these simulations. The system architecture is complex due to the limited space available. Therefore, there was a need for simulating the assembly process of the components using JACK; the simulation demonstrated that the established assembly sequence is feasible. The next step was the manufacturing of a prototype of the acrylic hemispheres. A 5-axes CNC machine-tool center was used to machine the hemispheres and the air bearing. The dimensions of the products were verified using a coordinate measuring machine. The measurements of the hemispheres and air bearing showed that the machining parameters established for the manufacturing were adequate. Moreover, the production of the prototype demonstrated that acrylic may be used for the hemispheres.

***Keywords**: Air bearing, attitude control simulator, manufacturing, assembly.*

1. INTRODUCTION

The principal aim of this paper is showed part of a development program of a prototype simulator based on an attitude air bearing with three degrees of freedom in rotation. In this paper, will be addressed mainly to define the system architecture, preliminary design of components, design and manufacture the air bearing.

This prototype serves as a test bench for other works of a research Project called ITASAT – University satellite. It will work as follows: an acrylic sphere of diameter 350 mm, will be suspended by the aerostatic effect, having in its interior the components (Wheel reaction, gyros, system balancing, fixture device, integrated circuit boards and battery power) which compose a satellite. The air bearing stator will function of “cot” to acrylic sphere. When you inject air the air bearing stator the sphere will be suspended, as if floating (simulating a satellite in orbit). By means of reaction wheels will be possible to control the rotation movements of this sphere suspended in three degrees of freedom, and the gyros carry out the measurements of angular movement, allowing that a controller keep the equilibrium (static sphere)

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and correct the prototype plane of rotation, based on the fact that a Wheel with large angular speed keep always the same orientation in inertial space, even with the constantly change of position (attitude).

The choice of a spherical shape for the prototype was due to ease of construction for the spherical shape to air bearings and either to facilitate the rotation movement from the system, restricting the translations. Either it is easier to control the system because there aren't obstacles and the friction is very low, meaningless for this situation. Another great concern when designing this system to differentiate it from existing, scale it was on low torques, the large rotations and almost null friction.

In Virginia Tech (Schwartz, 2003) Jana L. Schwartz, Mason A. Peck e Christopher D. Hall, part of a group that develops research on satellite Simulator already 45 years ago. Among the various research performed, this group developed a Project called AIMBUS, an attitude simulator like this that will be described in this paper.

The project AIMBUS has as principle a submarine, has the means to work the water and no the air, a glass sphere, with three reaction wheel, a camera and a computer. In addition to simulating the attitude, had biological aims, therefore a camera. This sphere was launched in aquatic ecosystems with purpose of shooting the different environments, but this prototype lost its function when placed in high depth (Wang, 2001).

2. DEFINITION OF SYSTEM ARCHITECTURE

This prototype will be composed of two hemispheres with 350 mm diameter, manufactured in acrylic. After the manufacturing, the hemispheres were glued. The spheres have an internal cavity where are inserted: three reaction Wheel, two gyros, two balancing devices, control boards, fixture devices and battery.

The architecture is defined as the physical components are related, and how the simulator can be modified. Arrangements for integrated prototype, a change may affect different functions, making necessary changes in several related components.

All products are composed of one or more materials. These materials have mass and must be manufactured in order to obtain some form of components. An improperly chosen material can lead to component failure and also the unnecessary costs. The selection of materials that meet the specifications target in an acceptable cost was an important part of the process of this product development.

After selecting the material, it is extremely necessary to know the shapes and sizes in which these materials are commercially available in order to avoid problems.

Table 1. Characteristics for the simulator components.

Components	Dimension (mm)	Mass (kg)	Material
Hemisphere superior	radius = 175	6.41	acrylic
Hemisphere inferior	radius = 175	7.26	acrylic
Reaction wheel	diameter: 98 thickness: 10	0.32	Steel
Gyros	length: 62 width: 60	0.40	Aluminum
Battery	diameter: 13 length: 43	0.32	Aluminum
Fine balancing system	length: 246.5 width: 24.7	0.21	Steel /aluminum/lead
Vertical balancing system	diameter: 30.4 thickness: 15.2	1.25	Steel

The total mass estimated for the whole set is 17.5 kilograms, in addition to the components cited in the table above, the mass of other items should be taken into account to balance the simulator is the best possible way. Other components that should consider the masses: clamping systems, screws and wiring.

2.1. Attitude Control

The purpose of determining the attitude is to get the orientation of a spacecraft, in case of the sphere, for an inertial reference system, whose origin can be the center of the earth, or a specific direction. Basically, it uses attitude sensors, which are devices that determine the attitude of a satellite measuring its orientation with respect to the reference. In this prototype two gyros will be the role of sensors and three reaction wheels are the actuators.

2.2. Assembly System

For assembly design, several aspects must be considered, such as: design for flexibility, streamlining functions, feed processes, insertion, and their structural relationships. This was a phase of planning for the assembly of a prototype simulator for attitude control with air bearing in three degrees of freedom (Figure 1). For these tests were used as tools, the Design for Assembly (DFA) and JACK software which is used to perform simulations in virtual environments. With the use of these tools evaluated the design failures that would be notice only in the manufacture or assembly of the system (Souza, 2008a).

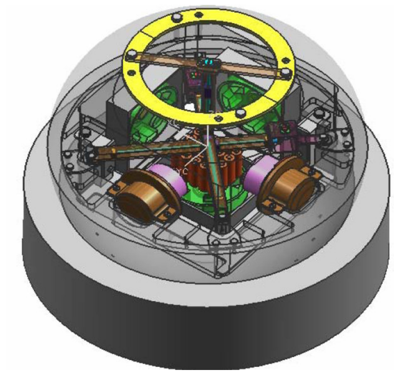

Figure 1. Arrangement of elements assembled.

The importance of using the Jack software and the DFA method in this work is due to difficulties found in the prototype assembling, as simulator designed is composed by several components and in its internal space is very small. It is extremely necessary to establish the correct sequence for assembly, to avoid possible errors before the manufacture of components, so that the proposed architecture does not interfere in the operation of the control attitude simulator. To make these analyses, were used as indicators: time for assembly and viability of the assembly of all components produced. Initially, has been developed the mapping for all components that will be allocated in available space from simulator and then were proposed possible architecture models for the system (Souza, 2008a).

3. PRELIMINARY COMPONENTS DIMENSIONING

3.1. Gyros

These are mechanisms that contains a heavy wheel that turn a certain speed, and supported in bearings that have a low rate of friction, or a wheel rotation whose is maintained by a torque motor, whose axis is fixed by special coupling type balance (gimbal), and allowing freedom of axis movement. In turn, the wheel resists any attempt to modify its rotation plan. As it is supported by a series of rings arranged on bearings, keep your rotation plan regardless of the position of set.

It is appropriate to install the gyros next of the gravity center (CG), because it absorb the vibration and the allowance of the system, and due to the inertia.

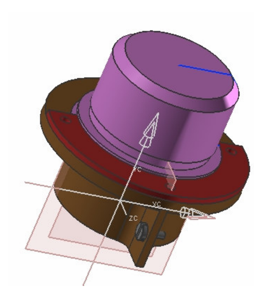

Figure 3. Model of the gyros that will be used (Junqueira and Barros, 2003).

The two gyros that will be part of the simulator were designed and manufactured by the laboratory CTMSP/ARAMAR (Fernando Castro Junqueira - Centro Tecnológico da Marinha em São Paulo).

3.2. Reaction Wheel

The reaction wheels are made basically, by an electric motor which turns a wheel, both common and supported in bearings placed in a box, forming a compact set and easy clamping anywhere in the structure of the satellite.

As in the beginning of the gyro the reaction wheel is based on the fact that a wheel with a certain angular speed keeping the same orientation in inertial space, even if the satellite where it is in change of attitude. However, as the axis of rotation of the wheel has no freedom of movement to be fixed to the satellite body, there will be a reaction from this to the attitude change is increase or decrease its rotation speed. So when changing the rotation speed of the wheel the satellite will react to a change of attitude, a change of rotation speed of the reaction wheel applies a torque on the spacecraft.

The three reaction wheels that are used in the prototype was designed based on catalogs and models of reaction wheels of the market offers and through research into satellites already developed and under development.

The distribution of the inertia moment from turn part has 90% in the wheel and 16% at the central part. The wheel must rotate with a maximum angular velocity to 9000 rpm, and the nominal angular velocity will be 5000 rpm. Without the tension introduced by adjustment of the cube and the concentration of tensions in drilling, the maximum stress on the disc is:

$$\sigma_t = \rho\omega^2 \frac{3+\mu}{8}\left[2r_0^2 + \frac{2(1-\mu)}{3+\mu} r_i^2\right] \quad (1)$$

where ρ is density of the material, ω is the angular velocity; μ is the Poisson coefficient; r_0 e r_i are the external and internal radius, respectively. The value obtained is 0,6544 kgf/m^2, which dispenses more checks.

The time duration of the experiment will be 5 minutes. The maximum error established for the design of the reaction wheels is 8 μm. Considerations for the design of the reaction wheels:

$$\vec{T} = meg \quad (2)$$

$$\vec{L} = \vec{T} \quad (3)$$

$$\int_{t1}^{t2} \vec{T} dt = \Delta \vec{L} \quad (4)$$

$$\Delta L = \int_0^{t1} megdt = mge\Delta T = 125.8.300 = 300 mNms = I\Delta\omega \quad (5)$$

$$\Delta\omega_0 = 4000 rpm \quad (6)$$

$$I = \frac{6.0,3}{800.\pi} kgm^2 = \frac{1,8}{800.\pi} = 7,16.10^{-4} kgm^2 \quad (7)$$

where e is error of gravity system that to make up for wheel, m is the mass of the reaction wheel, g is the gravity acceleration, T torque, ΔL is variation of the angular moment, I is inertia moment and e ω is angular velocity. The motor used is the manufacturer Faulhaber.

3.3. Fine balancing system

The simulator balancing process was made by one of the software tools included in the NX4 package. To ensure a system refined balance it was developed a device for the refined balancing, or a mechanism to help small adjustments in the balancing. This system consists in an acrylic tube, with a conical gears mechanism, and one axis where a moving mass can be displaced. The operation of this device is done through a hole in the upper edge of the sphere, where a screwdriver adjust the positioning of the mass that will move through the axis, the mechanism of two conical gears are moving the mass until the appropriate position to system. In the prototype will be placed three of these devices, one on each axis (x, y, and z) to ensure more precise balancing.

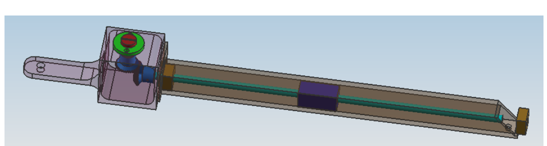

Figure 4. **Fine balancing system.**

4. DESIGN AND MANUFACTURE OF THE SYSTEM

4.1. Design and Manufacture of the Hemispheres

Through various surveys conducted among the possible materials that could be used for the manufacture of the sphere came to conclusion that the acrylic would be the best option because the basic properties that it presents. The choice of acrylic was not by chance, because this is a transparent material that is distinguished by its qualities of durability and resistance properties.

It is a material which softens at a temperature of 80^0C to 100^0C, the friction resulting from the machining process can cause enough heat to stick in the tool. Another carefully is to be taken in the output of the cutting tool from the acrylic piece, because depending on output of the tool the piece can be spall.

The acrylic have a very important limitation that be considered. Its stability is not ensured. The acrylic can had dimensional variations and significant ways over time, especially if subjected changes temperature and humidity. This would be critical to the air bearing, as this type of mechanical system requires quality of dimensional and form to work with relative clearances between rotor and stator on the order of a few micrometers.

In the specific case of this project, no search operation of air bearings in its carrying capacity limit and stiffness limit, the work clearance will be much higher, allowing that imperfections in the shape of the acrylic sphere is considered acceptable without commitment to the operation of the system (Souza, 2008b)

To further develop the project, was chosen primarily to manufacture a pilot piece of the sphere and the pilot air bearing, to avoid irreparable mistakes in the final pieces. Therefore, in this article are the results of testing and manufacturing of pilot parts.

The clamping of the piece machined is one of the most important functions during machining process, because it ensures the quality of the process.

It can not use excessive pressure in the clamping to not cause fissure. Moreover, the cooling of pieces is essential in machining. The chips should always be removed, not to join the play. The chips must be removed to no stick to piece. The tool speed depends on the diameter, type of finishing and accuracy desired, and conditions of machining.

The machining pieces need to low error of shape and high precision, as will be part of an air bearing.

In the machining process were used different cutting path (spiral and radial) and two machining process (milling and turning). In the milling varied the cutting path, one made in a spiral and the other made in radial, both starting at the edge of the cavity, to eliminate unnecessary exits of tool. The choice of two types of cutting strategies was to see which one gives better roughness surface and smaller errors of form. The other cutting parameters chosen were equal (Souza, 2008b).

The acrylic is a material which has low thermal conductivity, the heat generated during machining process is almost all absorbed by the cutting tool and another part with removed by cutting fluid (Fig. 5). This accelerates the wear of cutting tools and, with use of high speed and high advances, causing damage in the machined surface.

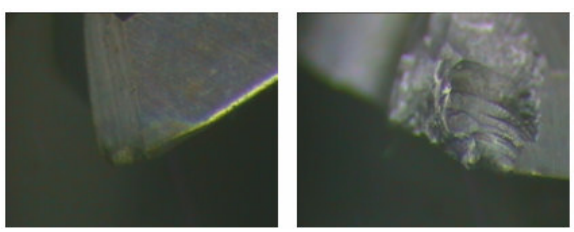

Figure. 5. Milling cutter before and after machining of acrylic (Souza, 2008b).

If the acrylic chips return to the cutting zone, the increased occurs of the tool wear and a worsening of the surface finishing, because the chip starts to welding on the piece face.

The turning process, when compared to milling is a process where there is not interrupted cutting, ie cutting tool does not enter and exit the piece continuously, which results a better finishing surface of the piece.

The clamping system used was limited, since the measurement of the mounted sphere presented relative error in orientation between the two spherical calotte in order of up to 0.12 mm, which must be corrected for future works.

4.4. Design and Manufacture of Air Bearing

Air bearings are components of mechanical systems that have a high quality of trajectory on their movements, which is essential in specialized equipment and three dimensional measuring machine and machine tools for ultraprecision machining, among others.

Its operational features depend only on its manufacture quality, and should have low errors of shape and dimensional.

Air bearing using a thin film of gas at high pressure to take loads. The air has very low viscosity, the allowance between the bearing surfaces are very small, are around 5 to 25 µm.

One of the principal aim of the air bearing is to correct choose of the size of power restritor of air associated with an optimization of the clearance for get a optimal condition of stiffness, taking into account a range of load applied during the system operation the bearing. Projects wrong result in low stiffness, inefficient operation and high manufacture cost.

The diameter of the restritores orifices are of 0.18 mm. The air power restritores must be without undercut, because the difficulty of manufacture of other types of restrictors prevent their use.

Table 4 presents the basic equations for the correct sizing an air bearing and the results obtained for the simulator attitude project.

Table 2. Sizing the air bearing.

Parameter	Equation	Values
Maximum stiffness (N/µm)	$k_{\max} = \dfrac{0{,}29.\pi\left(R_0^2 - R_i^2\right).\left(P_0 - P_a\right)}{h_0}$	129,432 N/µm
Angular stiffness (N/µrad)	$K_A = \dfrac{0{,}23.\pi.\left(R_0^2 - R_i^2\right).R_0.R_i.(P_0 - P_a)}{h_0}$	1,026 N/µrad
Maximum load capacity (N)	$W_{\max} = 0{,}26.\pi.(R_0^2 - R_i^2).(P_0 - P_a)$	9283,43 N
Air flow	$Q = \dfrac{0{,}27.h_0^3.P_0^2}{6{,}84.10^{18}.\ln\left(\dfrac{R_0}{R_i}\right)}$	1,248 l/min
Diameter of the restrictor orifice (mm)	$d_f = \dfrac{2.\Lambda_s \xi.h_0^2.P_0}{31{,}55.10^6.n.\ln\left(\dfrac{R_0}{R_i}\right)}$	n = 20 holes

The results were obtained for df = 0,18 mm (diameter of the orifice restritor) and h_0 = 8 µm (the bearing clearance). The stator is principal pieces that composed the set of air bearing, this is to ensure that the operation and movement of the acrylic sphere. The stator can be seen through Figure 6.

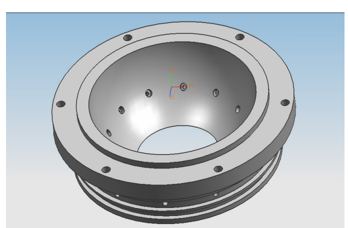

Figure 6. Stator – piece that supports the acrylic sphere.

Through the theoretical results found in table 4, it finds that the theoretical carrying capacity for this bearing is 9283,43 N. As the sole function of supporting the load bearing of the simulator is to support the weight of the set itself, without any variation of the load during operation of the system, it can conclude that it meets with much bearing on the condition of loading. This extrapolation of the load bearing capacity was so purposeful. Carrying capacity in an air bearing is directly related to the work bearing clearance. Thus, in a natural way, as there is no restriction on position in the vertical direction of the simulating operation, the acrylic sphere with all other components will take a balanced position of his body with a much higher work clearance to 8 micrometers in design. This new clearances will possibility that shape and geometric errors in the acrylic sphere are accepted into the system, without compromising performance.

The tolerances dimensions and manufacture of air bearings are very narrow, requiring special methods and manufacturing machine, along with a high quality control.

The sizing of an air bearing is based on fixed values of the dimensions imposed by the project, the size of the acrylic sphere.

The stator from bearing was done manufacture in aluminum due its resistance and to present machining features known.

To achieve low errors using the technique of components lapping, after machined. The lapping was done with a thin oil MA-5 (70% in volume) and dispersed particles of silicon carbide with a granulometry of 3 μm (30% in volume).

4.3. **Metrological Evaluation Set**

This step was to measure the bearing and hemispheres with the basic objectives of:

- Obtain information on the errors of shape and the bearing surfaces and acrylic manufactured hemispheres;
- Qualify the manufacturing operations, using measures of roughness surface.

For quantify manufacturing operations, using measures of surface roughness. To quantify the dimensional quality of machined pieces used a measuring coordinates machine (MMC), from Mitutoyo.

In this study the roughness surface was obtained by three techniques, values of Ra (average roughness), Ry (maximum roughness) and Rt (total roughness) were obtained using a complex roughness surface measuring machine, CNC Form Measuring Instrument Series (Fig .7), the manufacturer Mitutoyo also.

Figure. 7. Evaluation of roughness complex surface.

To measure the roughness of three acrylic hemispheres, were measured 4 different regions: the 0 °, 90 °, 180 ° and 270 ° in order to check the variation of the roughness values in different regions of the machined hemispheres.

Figure 8 shows the results obtained in the pilot acrylic hemispheres machining. It was observed that the generated surfaces in the three pieces (spiral milling, milling radial and turning) showed significant differences in finishing surface. The milling hemisphere with the spiral cutting strategy presented larger steps, the hemisphere that used radial strategy presented a less rough surface compared to before. But as expected, the average roughness of the turned hemisphere showed better surface quality, but the radial milling showed roughness Ry and Rz with the superior turning quality, indicating a lower depth of valleys on the piece surface (Souza, 2008c).

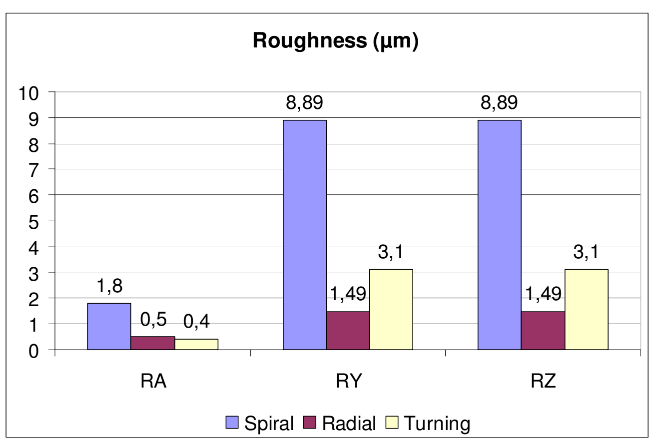

Figure. 8. Surface finishing of the stator.

In machining of acrylic hemispheres was adopted a roughness theoretical of 0.5 μm that can be know on other air bearing projects, as an air bearing designed by Pereira (1998). In this project, the radial milling and the turning attended the pre-defined specifications.

Table 3 presents the geometric measures of acrylic hemispheres and aluminum stator: average diameter, experimental standard deviation and the circularity value.

The sphere diameter, although it was scaled to a nominal diameter of 350 mm, all showed lower value measured, but all within the tolerance of design GD&T (± 0,50 mm).

Table 3. Geometric evaluation of machined hemispheres and stator.

	Spiral milling	**Radial milling**	**Turning**	**Turning of the stator**
Mean diameter:	349,84 mm	349,86 mm	349,96 mm	351,64 mm
Standard deviation:	0,10 mm	0,10 mm	0,01 mm	0,26 mm
Circularity:	0,15 mm	0,14 mm	0,04 mm	0,08 mm

Observe that the turning process was near to the nominal value in addition to lower experimental standard deviation and lower circularity value.

In this case the geometric evaluation was only research, because it will suffer a second manufacturing process, that is: application of epoxy resin and lapping in order to adjust it to the shape of the acrylic sphere in the stator cell (Souza, 2008c). To facilitate the resin adherence, the finishing required for this surface is rough, as seen in Figure 9.

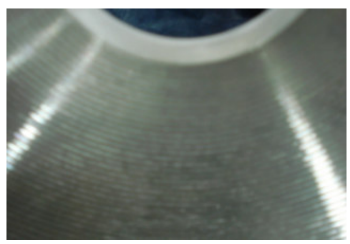

Figure. 9. Details of the surface finishing of the stator (Souza, 2008c).

The machining time of acrylic hemispheres were also verified and analyzed in this study and are presented in Table 4.

Table 4. Machining Time of acrylics hemispheres.

	Spiral milling	**Radial milling**	**Turning**
Machining Time	4 hours	6 hours	2 hours

It can be observed that the turning process is what brought greatest advantage with respect to the machining time.

A greatest difficulty in the process manufacturing was obtaining the necessary clearance of bearings to match the rotation axis of acrylic sphere with stator geometric axis. Because in case of no possibility, the acrylic sphere can orbit around the stator geometric axis causing a residual unbalanced in the system, affected the simulator functioning.

Another factor was to obtain a condition of roughness in acrylic machining, to ensure the lapping process without change in the hemispheres shape. The results showed that these difficulties were eliminated due to design specification and of the manufacturing processes were used.

The roughness measurement helped to conclude about the effect of the machining strategy with acrylic. Effectively, a later process of lapping is necessary for finalization spherical cap, this result reduced the time lapping (Souza, 2008c).

5. CONCLUSIONS

The intention of this work was the design, manufacture and assembly of the attitude simulator (sphere and bearing), and to achieve these objectives were used: tools for project planning, the DFA (Design for Assembly). From a good planning can be developed throughout the architecture, dimension and balancing of the system, preventing future problems that will certainly affect the subsequent stages of design, in the manufacture and assembly of pieces. This project is in the final stage of pieces lapping, since all items have been successfully implemented (manufacturing and assembly). The final pieces were manufactured using the best results in tests with the pilot pieces that were described here, so the results met all the items of the planning done.

Also presented the development of the manufacture process and surface qualification from the prototype. Through machining of three acrylic hemispheres (pilot pieces) it can get the best fabrication.

The turning process is that brought the greatest advantage over the other. In addition to meeting the specifications of the project, was the process that was performed in 25% of the time of the radial milling.

But the use of HSM technology has found that the radial milling also satisfy the requirements for finishing surface and geometric tolerance of acrylic spheres, reaching similar results to the turning process with benefit appeared significant in the roughness parameters Ry and Rz, around 50% better than the turning process.

This apparent advantage for air bearings may be a factor that can positively to influence the functioning of the air bearing due to the values of Ry and Rz information about on the average distribution of surface, indicating lower numbers of valleys in the roughness surface. Is expected that the lapping process is easier than just the Ra parameter, but in practice this factor has not been observed. These advantages should be subject to future work.

The spiral milling showed the worst results in the acrylic machining, with a discarded process in this project.

Already in the stage of assembly is considered as most relevant data to time decrease of assembly and reduction in the number of components. Table 1 shows the data input and output using the simulation with Jack software. The input data are first designed and the data output is generated by the simulation option.

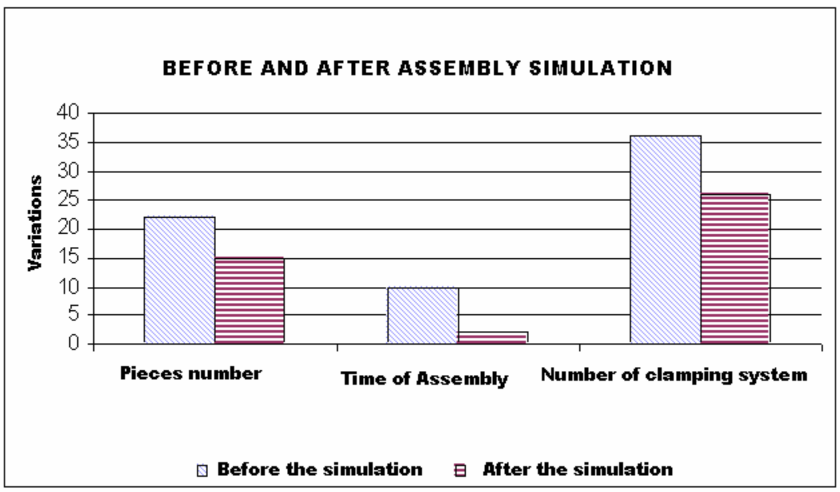

Figure 10 – Data input and output of the simulation model.

At the beginning of the design, before implementation tool DFA, the prototype would have a total of 22 pieces after the used DFA tool to reduce the number of piece to 15. Seven pieces were designed unnecessarily. With this reduction in the number of pieces, the project becomes more cost in manufacture time and assembly of the system.

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