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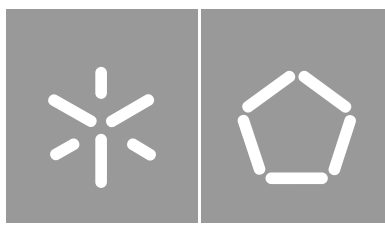


Universidade do Minho
Escola de Engenharia

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Implementation of a Cleaning System in an Automatic Machine

February 2021



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Escola de Engenharia

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Implementation of a Cleaning System in an Automatic Machine

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Work developed under the supervision of

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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ABSTRACT

This project consists of the architecture, design, production, and implementation of a cleaning system applied in a machining centre responsible for the manufacture of accessories with orthotic or prosthetic applications used in the "Padrão Ortopédico" company. Thus, it was necessary to carry out a mechatronic project.

Initially, it was necessary to keep in mind a theoretical framework on the subjects to be dealt with during the project. For this purpose, several bibliographies on the theme were studied.

The CNC machine to be improved was also intensively investigated in order to get to know it in its entirety and to gather all possible information about it since there were no past records. The result of this process was to point out its weak points and highlight the problem of waste accumulation inside the machine which would have to be solved with a specific Hoover.

During the construction of the vacuuming system, there were several parameters that had to be taken into consideration. In an initial phase of architecture and design, a model of a cyclone Hoover was selected with the suitable relationship between its dimensions. Its constituent parts were also designed and printed three-dimensionally respecting the structure chosen.

Before the production of the parts constituting the Hoover, its assembly was tested through virtual simulations of computational fluid dynamics.

In a final phase of the project, the integration and verification took place at the site defined within the CNC, and it was verified that the system was working. The operation of the Hoover occurs without any malfunction. It takes place at the same time as the machine operations, thus resulting in a possible and positive validation and transition of the project.

Based on all the work done it is possible to criticise it positively and negatively thus pointing out possible improvements that could be made to the vacuuming system in the future.

Keywords

Prosthetic, Orthotic, CNC, Mechatronic, Project, Vacuuming, System.

RESUMO

Este projeto consiste na arquitetura, conceção, produção e implementação de um sistema de limpeza aplicado a um centro de maquinagem responsável pelo fabrico de acessórios com aplicações ortoprotésicas utilizados na empresa "Padrão Ortopédico". Assim, foi necessário levar a cabo um projeto mecatrónico.

Inicialmente é sempre necessário ter em mente um enquadramento teórico sobre os temas a tratar durante o projeto. Para este efeito, foram consultadas várias bibliografias sobre o tema.

A máquina CNC, a ser melhorada foi também intensamente investigada a fim de a conhecer na sua totalidade e de recolher todas as informações possíveis sobre a mesma, uma vez que não existiam registos sobre a sua funcionalidade e características. O resultado deste processo foi evidenciar os seus pontos fracos e realçar o problema da acumulação de lixo dentro da máquina, que teria de ser resolvido com um aspirador de pó específico.

Durante a construção do sistema de aspiração, houve vários parâmetros que tiveram de ser tomados em consideração. Numa fase inicial de arquitetura e desenho foi selecionado um modelo da relação entre as dimensões de um aspirador de pó do tipo ciclone. As suas partes constituintes foram também concebidas e impressas tridimensionalmente, respeitando o modelo escolhido.

Antes da produção das peças que constituem o aspirador de pó, a sua montagem foi testada através de simulações virtuais da dinâmica do fluido computacional.

Numa fase final do projeto, a integração e verificação teve lugar no local definido dentro da CNC, constatando-se que o sistema estava operacional. O funcionamento do aspirador de pó também ocorre sem qualquer anomalia de operação. Ocorre ao mesmo tempo que as operações da máquina, resultando assim numa possível e positiva validação e transição do projeto.

Com base em todo o trabalho realizado, é possível fazer uma reflexão crítica, valorizando quer aspetos negativos quer positivos apontando, assim, possíveis melhorias que, no futuro, poderiam ser feitas ao sistema de aspiração no futuro.

Palavras-Chave

Ortoprotésica, CNC, Mecatrónica, Projeto, Aspiração, Sistema.

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ABBREVIATIONS, ACRONYMS AND UNITS

& – And	m ² /s – Metres square per second
~ – Approximately	min – Minutes
2D – Two-dimensional	mm – Millimetres
3D – Three-dimensional	mm ³ – Cubic millimetres
A – Ampere	MPa – Megapascal
AH – Ampere per hour	Mx – ISO standard dimensions for screws and bolts
CAD – Computer-aided manufacturing	N – Newtons
CFD – Computational fluid dynamics	n.d. – No date
cm – Centimetres	N/m ² – Newtons per metres square
CNC – Computer numerical control	Nm – Nanometres
DC – Direct current	°C – Degree Celsius
e – Natural exponential function (equivalent to x10)	Pa – Pascal
et al – And others	PLA – Polylactic acid
g – Grams	rad – Radians
GRBL – Garble	rad/s – Radians per second
h – Hours	rpm – Revolutions per minute
kg/m ³ – Kilograms per cubic metre	STL – Stereolithography file format (Standard Triangle Language)
kg/s – Kilograms per second	Un. – Unity or unities
LCD – Liquid Crystal Display	UV – Ultraviolet
m – Metres	V – Volts
M – Millions	W – Watts
m/s – Metres per second	

LIST OF SYMBOLS

$^{\circ}$ – Degrees

\varnothing – Diameter

ν – Kinematic viscosity

ρ – Density

ω – Rotation speed

1 INTRODUCTION

This dissertation is about the implementation of a cleaning system, in an automatic machine, used in the company "Padrão Ortopédico" for the manufacture of accessories with orthotic and prosthetic application. For better understanding, the thesis is structured into coherent chapters that follow a logical and organised breakdown of the whole process of the CNC machine and of the prototype equipment, designed to address the problems that arise inside the machine.

Resultant in a mechanism integrated in the machining centre it is responsible for the aspiration of the particles released during its operation.

1.1 Background

The automation of tasks is the future, principally when it comes to manual functions that can harm those who perform them. This is why the role of automatic machines is so important, mainly in industry. However, like any human being, mechanical systems also need to be analysed and checked to see if they are capable to operate without developing any problems.

The studied automatic machine, although apparently healthy, presents limitations regarding its correct cleaning function, which later, if not solved, would give rise to new diseases.

In view of this, the purpose is to apply a device capable of suctioning the machine correctly, irradiating as much as possible all the scattering of trimmings inside the machine.

As the operators employed by the company do not have much knowledge in the area of mechanical and electronic systems it is intended to be easy to handle.

1.2 Objective

The most urgent and important problem to solve found in the CNC machine is that the suction method found was totally impractical since its entire interior was dirty with foam particles. It is in this problem that lies the whole objective of the work carried out.

The machine used by the company was designed and assembled for all the specific functionality it performs. However, there was no information about the equipment, which has made it more complicated and time-consuming to understand the whole organism. That is why the complete study of the machine

was so important in order to fulfil the purpose of including in it a suction system that would be of accessible use and easy to implement.

During the project, smaller but equally important objectives were also considered, such as spending as little raw material as possible, using recycled materials or components, thus reducing waste. In addition to reducing the costs associated with the project being a priority, the focus has also been on selecting local businesses to meet the needs as suppliers of necessary components.

1.3 Dissertation Structure

The dissertation is divided into six chapters organized in such a way that it is easy to consult something specific in the document or to read from beginning to end understanding the chronological sequence of events. Acquiring the order portrayed below.

In chapter 1 it is possible to find an introduction to the project which includes the framework, objectives and information about the company where the action development took place.

Chapter 2 contains all the information necessary for an ideal framework on the subject. These key points are essential for understanding automatic machines, designing mechatronic projects and also allows the reader to learn more about the area of prostheses and orthoses.

Chapter 3 gathers together all the information to obtain on the existing machine in the company and studied in its entirety. This includes all the interpretation of the CNC from the small parts that make it up to how they work together on a general level.

Chapter 4 is the core of the project. This is where the entire project is reported including all the good areas and areas in need of improvement in the design, simulation and construction of the suction system are recorded.

Chapter 5 describes the conclusion reached after the final phase of the project. It is always necessary to do more to improve even what seems to be well done, possible future work and improvements to the suction system are also presented.

1.4 Partner

“Padrão Ortopédico” is a Portuguese company created in 1983 who works entirely in manufacture and fitting of prostheses, orthoses and technical aids. The main focus on the service provided is the well-being of those who seek better quality life and comfort even with adverse physical conditions.

This company played a key role throughout the dissertation creation process. It provided its workspace such as the equipment and materials needed to develop the aspiration system. It also allowed one to gain the experience and knowledge for the working world, mainly in industry.

Although it focuses on the area of health and appears to act in a field far removed from mechanics or electronics, it does not mean that there can be no link between them. This proximity and exchange of knowledge between the different matters is indispensable for both parties and is shared in the company's workplace.

2 THEORETICAL CONCEPTS ABOUT AUTOMATION, CNC TECHNOLOGY, SUCTION SYSTEM, METHODOLOGY IN MECHATRONIC PROJECTS, PROSTHESES AND ORTHOSES.

The presented chapter refers to the importance of the automatized manufacturing's role in the present world and how applies itself. It clarifies what defines a CNC machine with updated technology vision. This information is intrinsic to a theoretical outline on how the manufacture of parts uses the coordinate system, as well as the transmission occurs, through motors or spindles and the types and characteristics of these motors.

After, it reports about the operation of a solid particle suction system. This section also explores the area of prosthesis and orthosis too, as specifications and procedures for their manufacture.

2.1 Automation in Manufacturing

In the continuous evolution of mechanical production towards ever-greater automation, the existence of machines, controlled through computers, marks significant progress in the technology.

Automatized production is a field in exponential growth that can be construed by its perks and flaws in Table 2.1.

Table 2.1. Pros and cons of automatized manufacturing (Blue, 2013)

Pros	Cons
Production time reduced.	Less versatility.
Accuracy and repeatability increased.	More pollution.
Fewer human error.	Initial investment.
Better safety.	Redundant process/machine.
High volume production.	Maintenance and training.

When the topic is an automated fabrication, compared to the artistry, the time spent for the making, transport, or treatment of a product is a significant advantage that comes up immediately. These specs in combination with the elimination of malformations provides the company with superior economic growth.

From a different perspective, as the entrepreneur, Mark Cuban urges, automation is going to cause unemployment (Kharpal, 2017). Given that it is quite common opinion, this is where the company plays

a very important role in upgrading its manufacturing processes. Training the employees to operate the machining centres, implemented to eradicate hard-manual labour, is an acceptable way to maintain their job on the corporation and offer improved safety measures.

2.2 CNC Technology

Using a computer as a manufacturing controller has developed a vast field in production technology. The correlation between the machine tool and the programmed processor defines the CNC technology, and it can be adjusted based on the necessary task.

As the name implies, CNC devices are programmable, which means it can autonomously perform the manufacture duty without persistent human interference.

2.2.1 Coordinate System

Most of CNC machines use the cartesian coordinate system, which uses the X, Y and Z axes. The machine uses this system to move in a specific direction, by a specific plane.

It is possible to reduce the cartesian system to a numbered line. One point on the line is called 'origin', and the numbers on the left are considered negative and, on the right, positive.

If the three axes are combined in a 3D space, it results in an area for the machine to be able to move around.

The operator's interest is to figure all the space operable by the machine, using the 'right-hand rule'. The rule consists in pointing the third finger (counting from the left to the right) of the right-hand to the machine tool and observe the other two first fingers, forming a ninety-degree relation between them, as the Figure 2.1 illustrates (Deans, 2018a).

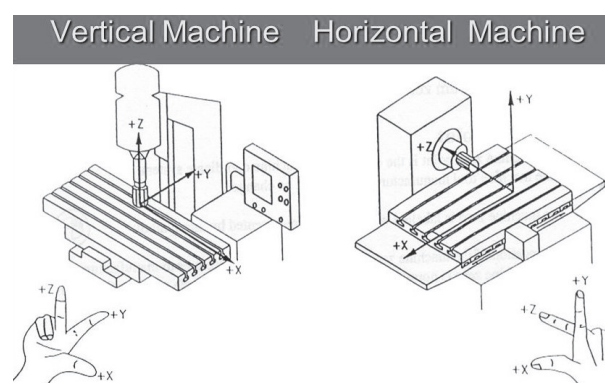


Figure 2.1. The 'right-hand rule' in vertical and horizontal machines (Deans, 2018a).

When interacting with a CNC, for the correct use of the coordinate system, it is necessary to establish an origin. In the production of a part, the origin can be any point of it, but it has to be convenient according to the operations to perform. However, these coordinates do not match those of the machine, thus

requiring offsets. A computerized numerical control machine uses work offsets in order to determine the desired coordinates, by the difference between the values from the work area and the machine's zero position.

Currently, the most common language used for interpreting commands is the 'G-code' and Table 2.2 demonstrates the letters that initiate some of these commands and their functionality.

Table 2.2. Numerical command addresses in 'G-code' (Deans, 2018b)

N	Block number.	I, J, K	Circular interpolation parameters.
G	Preparatory function.	F	Forward.
X, Y, Z	Displacement of the principal axes.	S	Number of spins of the tree.
U, V, W	Displacement of the secondary axes.	T	Tool number.
A, B, C	Rotary displacement.	M	Auxiliary function.

2.2.2 Driving Mechanisms

The part of the CNC system that follows the given command authentically it is called *servo*. When the *servo* receives a specific numerical instruction, it starts the rotation, which is transformed into a linear movement by a ball screw or belt that contributes to the axis drive. Followed by the numerical control commands, the velocity, and torque of this driving is *servo's* responsibility to control it. In Figure 2.2, it is possible to understand this mechanism applied to the translation of the working plate (Suh et al., 2008).

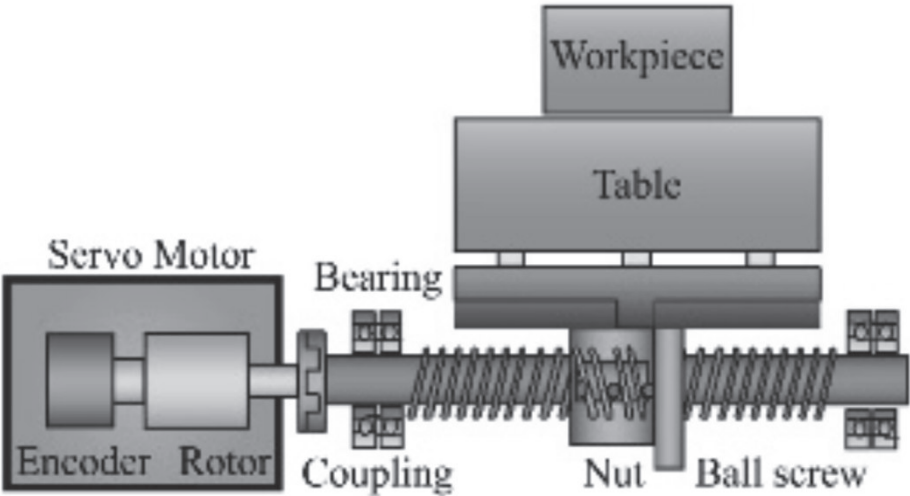


Figure 2.2. Servo driving mechanism (Suh et al., 2008).

If the objective is to have a rotation on the spindle instead of having movement on an axis, there would be a spindle motor accountable for conducting spin. This communication is across a belt involving pulleys, which its sizes determine the velocity ratio. Figure 2.3 illustrates the system (Suh et al., 2008).

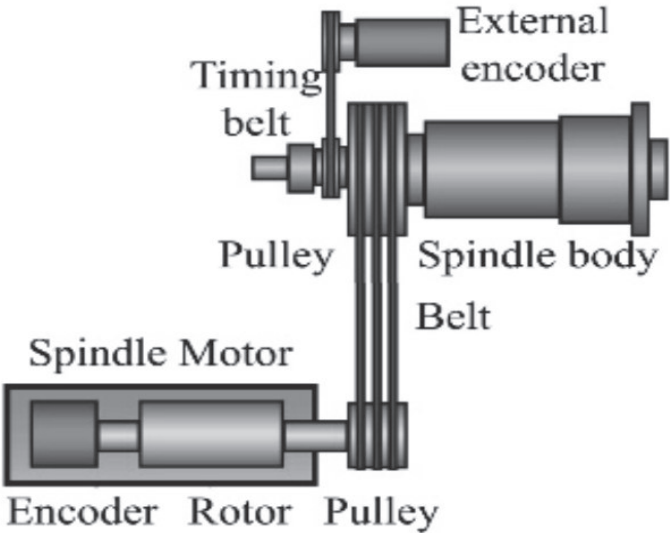


Figure 2.3. Spindle driving mechanism (Suh et al., 2008).

2.2.3 Driving Motors

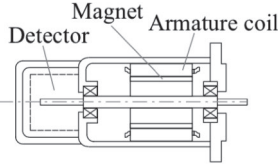
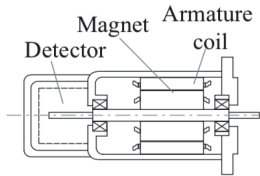
Driving motor is the word specified for the engines used on the driving mechanisms; it includes both spindle and *servo* motors. While the spindle motor requires high torque values and speed for the cutting of the part, the *servo* motor needs high torque and acceleration for moving the working axes.

In pursuance of having an agile response during the movement of the axes, the *servo* motor needs to control the position and velocity at low speeds continually. For this purpose, this type of engine requires adequate torque for stopping, rotation accuracy, and present good acceleration and deceleration properties . With this in mind, it is essential to know which *servo* motor is adequate for the machining process. Therefore, Table 2.3 provides the characteristics and scheme of different *servo* motors.

Table 2.3. Types of a *servo* motor (Suh et al., 2008)

Engine Type	Scheme	Features
DC <i>Servo</i> Motor		<ul style="list-style-type: none"> Speed based on the voltage applied. Wide velocity range. Self-starting. Low price. Reduced life expectancy. Demands maintenance frequently.

Table 2.3. Types of a *servo* motor (Suh et al., 2008) (cont.)

Engine Type	Scheme	Features
Synchronous-type AC <i>Servo</i> Motor		<p>Speed determined by the frequency of the applied voltage (not possible to control).</p> <p>Needs a starting mechanism on a single phase.</p> <p>Long life.</p> <p>Needs encoder or resolver.</p>
Induction-type AC <i>Servo</i> Motor		<p>Speed determined by the frequency of the applied voltage (difficult to control).</p> <p>Self-starting.</p> <p>Long life.</p> <p>Requires less maintenance.</p>

In comparison to DC motors, AC motors withstand higher current. Their use is more common for in-line productions, robots and other industrial applications that require high repetitions and high precision.

On the other hand, when it is preferential that an engine has high torque values in a static situation, at low speeds, instead of *servo* motors, stepper motors are used (Suh et al., 2008).

Stepper motors are DC motors that move in discrete steps. It consists of several coils that are organized according to groups, called phases. If energy is assigned to each phase sequentially, the motor would rotate, one step at a time (OpenlabPro, 2020).

It is possible to obtain exact positioning and speed control with this type of engine, through a computer. For this reason, stepper motors are preferentially chosen for applications that require movement control with high precision because of the drive control, due to their high pole count. Figure 2.4 elucidates the technology behind this category of the motor (OpenlabPro, 2020).

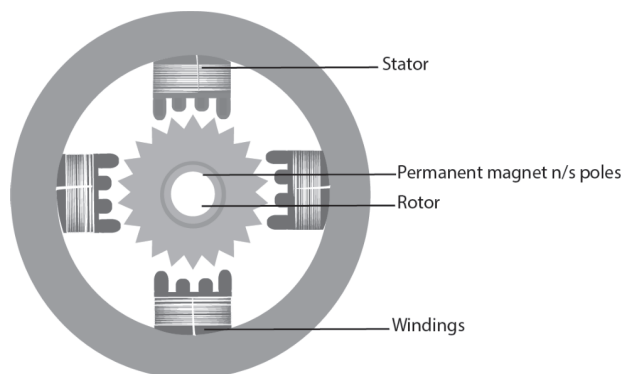


Figure 2.4. Stepper motor functionality scheme (OpenlabPro, 2020).

2.3 Solid Suction System

When a physical concept is mentioned as the transport of solid particles in a high-speed gas stream, the primary example that emerges is a standard household instrument, the vacuum cleaner.

There is no great admiration for the operation of a pneumatic conveying system. However, in order to design and build an installation that is reliable and efficient, it is necessary to appreciate the mechanism in detail.

There is a need to study and research the various characteristics of the solid flow in question. With the results obtained for efficient installation of the suction system, it is necessary to know how to analyse and classify them.

Since these steps are not sufficient for the projection of the entire system, the transport system must be correctly sized and tested empirically. Practical experience in the architecture of the equipment is highly relevant due to the existence of numerous variables that are difficult to quantify, such as the speed, size, shape and density of the solid particles such as pressure and temperature of the gas responsible for transport.

A suction system works by moving particles with a pressure equal or similar to the external environment to a lower pressure zone, such as a vacuum. From the practical point of view, a vacuum is defined as a space in which the pressure of the gas is low compared with what is normal - that is to say, atmospheric pressure (Chambers, 2005).

In order to create these low-pressure zones, it is necessary to know how to differentiate the vacuum according to the desired features. Table 2.4 shows the different uses and desired vacuum.

Table 2.4. Applications of Vacuum Techniques (Hoffman, 1998)

Physical Situation	Objective	Applications
Low Pressure	Achieve pressure difference.	Holding, lifting, transport pneumatic, cleaners, filtering, forming.
Low Molecular Density	Remove active atmospheric constituents.	Lamps (incandescent, fluorescent, electric discharge tubes), melting, sintering, packaging, encapsulation, leak detection.
	Remove occluded or dissolved gas.	Drying, dehydration, concentration, freeze-drying, degassing, lyophilization, impregnation.

Table 2.4. Applications of Vacuum Techniques (Hoffman, 1998) (cont.)

Physical Situation	Objective	Applications
Low Molecular Density	Decrease energy transfer.	Thermal insulation, electrical insulation, vacuum microbalance, space simulation.
Large Mean Free Path	Avoid collision.	Electron tubes, cathode ray tubes, television tubes, photocells, photomultiplier. X-ray tubes, accelerators, storage rings, mass spectrometers, isotope separators, electron microscopes, electron beam welding, heating, coating (evaporation, sputtering), molecular distillation.
Long Monolayer Formation Time	Clean surfaces.	Fraction, adhesion, emission studies, materials testing for space.

2.4 Methodology for Mechatronic Systems

Mechatronic products use interdisciplinary procedures during their process of conception. For a better approach during the creation its easier if it followed some topics.

'VDI 2206' is a guideline that gathers the steps to solve obstacles encountered or draw attention to important points that must be considered. These considerations are exposed in a wide way but in the end brought together in a V-shape model. The first scheme presented is a more generalized model, which represents in a macro way, as shown in the Figure 2.5 below (Verefn Deutscher Ingenieure, 2004).

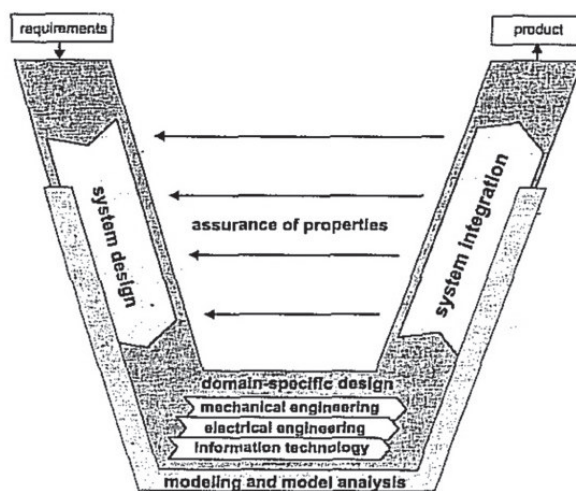


Figure 2.5. V-model as a macro cycle (Verefn Deutscher Ingenieure, 2004).

This model only brings together a simplified logical line of work. Initially, there is an analysis of the needs that must be met by the product to be developed. After this investigation, the design of the product begins, using mechanical, electronic knowledge resources and assistance with external information found, usually through bibliography or technologies (Verefn Deutscher Ingenieure, 2004).

Once the model of the product is completed, it is necessary to know if it would be well integrated by its users, because although tests or simulations have been carried out, the performance during use must always be predicted (Verefn Deutscher Ingenieure, 2004).

In 2018 a proposal for a new improved and more specific model was presented, represented in the following Figure 2.6.

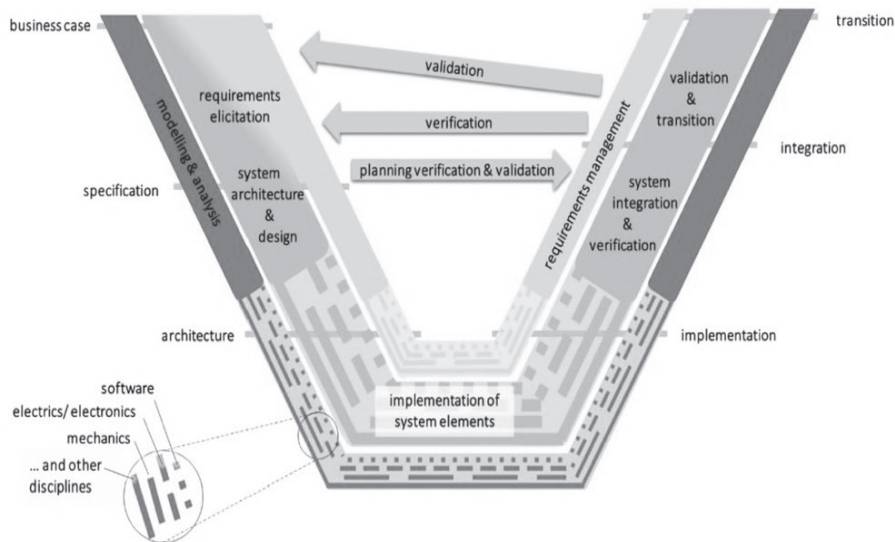


Figure 2.6. New V-Model as presented at 'DESIGN 2018 Conference' (Graessler & Hentze, 2020).

This scheme is separated in three strands. Central strand stands for the main activities and tasks, inner strand designates the management and the work with necessities and the outer strand characterizes the modelling and analysis activities (Graessler & Hentze, 2020).

The main activities and tasks include elicitation of requirements, structuring and analysis, which is the basis of the project development process. A survey of the needs and desires that the target audience retains, in a formal language and organized by lists or diagrams. This collection of data is subsequently converted to the visualization of the system in the next step (Graessler & Hentze, 2020).

In the next step all the interdisciplinary information from the branches connected to the product engineering is gathered. It is at this stage that the architecture and design of the product is defined. Uses as a basis the functional structure and the underlying action principles, bringing together the structure construction in the mechanical sense, signal flow and circuit diagrams in the electronic sense, as well as

the correct choice of a software program in its modules and components, with the best interfaces (Graessler & Hentze, 2020).

After the previous phase is completed, it is necessary to implement the system elements correctly designed, dimensioned and detailed. In order to reduce waste of raw material and unexpected errors, simulations are carried out. This step is of extreme importance because it has a lot of conditions that cannot be forgotten such as tolerances to ensure the correct dimensioning of the parts, calculations and dynamic and static analyses to guarantee a good lifetime and future behaviour of the product and planning of the manufacturing order (Graessler & Hentze, 2020).

Integration and verification of the system is the intermediary between the final validation and the implementation of the systems. Brings together all the conditions studied and confirmed in the different sub-systems of the product and ensure that they work correctly and synergistically (Graessler & Hentze, 2020).

In the final phase of validation and transition, a thorough check is made of all the requirements elicited for the correct use and total satisfaction of users. Whether this result is a final product, a prototype or simulation result, it is made known to the user in order to know if the whole v-model has been properly fulfilled and the project has been properly completed (Graessler & Hentze, 2020).

2.5 Prostheses and Orthoses

Prostheses and orthoses, although being terms usually associated with each other, differ in meaning depending on their usefulness. While a prosthesis replaces the lack of a missing part of the body, the orthoses aims to correct a malformation.

Regarding the design of the products the company yields, there are several techniques used. Some processes are still manual, and others are already automated, thus improving production time, among other advantages.

To be able to understand the importance of using different production methods, it is necessary to look at the core of how products are prepared.

2.5.1 Prostheses

Prosthetists' function is to assist patients who do not have a limb or part of it, designing, through the manufacture and adjustment of the prostheses or artificial members.

The responsibility of a prosthetist is carrying out the design to meet both functional and cosmetic needs according to the individual's specifications, following the correct selection of appropriate materials and components. The critical point is to execute the necessary moulds, measure and make changes according to a proper dynamic and static alignment under the patient's anatomy (Chui et al., 2020).

It is also necessary to analyse how the prosthesis fits and functions in the patient, such as teaching the patient how to take proper care of the prosthesis as represented in Figure 2.7.



Figure 2.7. Prosthetist adjusting a patient's prosthesis (This is Engineering, 2019).

Firstly, the part of the body where the prosthesis would be placed is involved in a film that facilitates the registration of bone areas with a marker. This would make it easy to withdraw the necessary measures. Measurements are usually referenced from readily palpable bony landmarks. The important anthropometric measurements are the residual limb length, successive circumferences, mediolateral and anteroposterior dimensions of the body segment for which the orthotic or prosthetic device is being prepared. The result values are based on the fixed distance from the indicated points. Figure 2.8 illustrates this part of the procedure.



Figure 2.8. Transcription of reference points.

Afterwards, the correction of the orientation points, the specialist uses a plaster ligature that is adaptable and mouldable by squeezing the grooves to obtain a more similar configuration to the patient's anatomy.

The bandages used, which can currently also be made of resin, are easy to handle due to their ability to water-moisten, resulting in no harm. Talcum powder is also sometimes used to help in the drying process. Figure 2.9 portrays this practice.



Figure 2.9. Moulding the limb features.

Customer welfare throughout the described plan is a priority. For this cause, during the cast cut, it is usual to assembly one tube for security measures as exemplified in Figure 2.10.



Figure 2.10. Insertion of a security tube.

After the mould is carefully removed, it is filled with plaster, which in turn gives rise to a positive model that would be central to the production of the prosthesis. This still quite rudimentary moulding technique has gradually been replaced by 3D scanners throughout the industry, including in “Padrão Ortopédico”. With the help of the scanner, represented in the following Figure 2.11, it is possible to convert a part of the body into a specific and detailed mesh, where all the relevant relief appears.

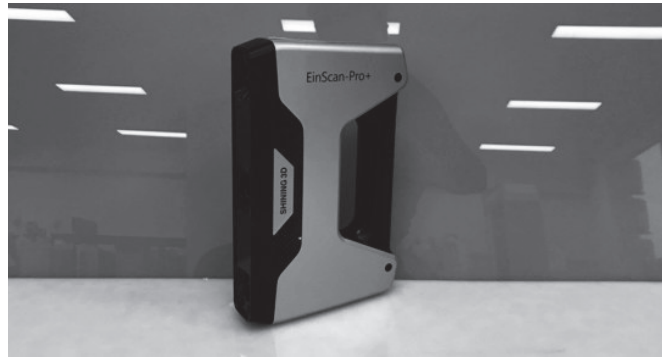


Figure 2.11. 3D Scanner from 'EinScan'.

Despite the appearance of prostheses taking place in ancient times, their technological progress was mainly during times of war, due to accidents or explosives, with immense injuries. In favour of the wounded have the opportunity to return to a relatively healthy life and not be unable to use that part of the body, there was a significant development on the field. The different type of prostheses, depending on where the amputation occurred, are classified as upper-extremity or lower-extremity prostheses, and their variations are represented on Table 2.5.

Table 2.5. Classification of prostheses (International Organization for Standardization, 2020)

Upper-Extremity Prostheses	Lower-Extremity Prostheses
Forequarter. Shoulder disarticulation. Transhumeral prosthesis. Elbow disarticulation. Transradial prosthesis. Wrist disarticulation. Full/Partial hand. Full/Partial finger.	Transfemoral (Above-knee). Transtibial (Below-knee). Ankle disarticulation (e.g., Syme amputation). Knee disarticulation. Hemi-pelviotomy (Hip disarticulation). Partial foot amputations. Van Nes rotationplasty.

2.5.2 Orthoses

Orthoses play a substantial role in orthopaedics and the rehabilitation care of individuals with different conditions and pathological disabilities of musculoskeletal origin. The musculoskeletal system can lose its functionality due to congenital, developmental disorders, acquired by an overuse injury, systemic disease, infection, neoplasia or trauma at any point in life (International Organization for Standardization, 2020).

As in making prostheses, it is necessary to take the measurements, strictly, to the area of the patient's body where the orthoses would be applied. For this to happen, it is possible to use the same manual method of creating a plaster mould as a reference.

According to 'International Organization for Standardization' terminology, orthoses are classified, by acronym, corresponding to the junction of the anatomical parts where they are placed (e.g., AFO are ankle-foot orthoses).

The type of existing orthoses is divided, according to where it would be placed, into three groups: upper-limb, lower-limb and spinal orthoses (International Organization for Standardization, 2020). The way in which the type of prosthesis is called within upper-limb and lower-limb groups is described in Table 2.6.

Table 2.6. Classification of orthoses (International Organization for Standardization, 2020)

Upper-Limb Orthoses	Lower-Limb Orthoses
Clavicular and shoulder orthoses. Arm orthoses. Functional arm orthoses. Elbow orthoses. Forearm-wrist orthoses. Forearm-wrist-thumb orthoses. Forearm-wrist-hand orthoses. Hand orthoses. Upper-extremity orthoses (with special functions).	Foot orthoses. Ankle-foot orthosis. Ulcer healing orthosis (UHO). Knee-ankle-foot orthosis (KAFOs). Knee orthoses (KO). Prophylactic, functional and rehabilitation braces.

One of the physical conditions whose recovery depends heavily on the use of a compensating orthosis is plagiocephaly.

Plagiocephaly is a term, of Greek origin, that translates to oblique head (plagios = oblique and kefalé = head) and is used to describe any abnormality, no matter the cause, of the shape of the head. Regarding the asymmetry of the skull, this condition describes the flattening of the occipitoparietal side (Villani & Meraviglia, 2014).

The leading cause of this phenomenon is the position that the baby is placed during the growth of its skull, as Figure 2.12 illustrates.

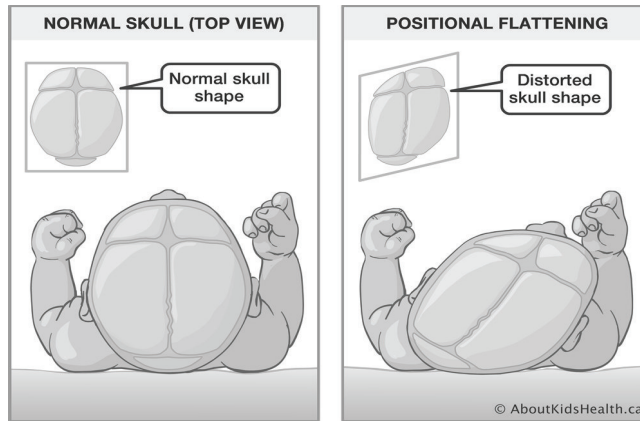


Figure 2.12. Comparison between normal and distorted skull shape (SickKids, 2020).

When new-borns have this physical condition, it can be classified in two different forms. There is the synostotic form, due to the premature closure of cranial sutures, and the nonsynostotic one, caused by extrinsic forces acting on the growing skull in the prenatal or postnatal age (Villani & Meraviglia, 2014). According to 'Argenta', the morphological classification of nonsynostotic plagiocephaly is divided into five types as represented in Table 2.7 and these depend on the asymmetry of the skull, position of the ear and deformity of the face.

Table 2.7. Classification of five types of plagiocephaly (Villani & Meraviglia, 2014)





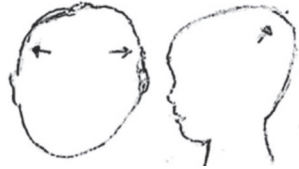
<p>Type I</p>	<p>Cranial asymmetry on the back of the skull. Degree of flattening can vary. Symmetrical ears and frontal bone. No protrusion or abnormal temporal vertical.</p>	
<p>Type II</p>	<p>Degree of posterior cranial asymmetry varies. Deformation on the midline and basicranium. Front part of the skull is not involved. Symmetrical forehead and face. No deformity compressions of the skull.</p>	
<p>Type III</p>	<p>Asymmetry on the posterior cranial. Malposition of the ear. Symmetrical face.</p>	

Table 2.7. Classification of five types of plagiocephaly according to Argenta (Villani & Meraviglia, 2014) (cont.)

<p>Type IV</p>	<p>Posterior cranial asymmetry. Malposition of the ear and frontal. Facial ipsilateral asymmetry.</p>	
<p>Type V</p>	<p>Posterior cranial asymmetry. Malposition of the ear. Asymmetry of forehead and facial.</p>	

For the reason of this physical condition being characteristic of new-borns, there is the advantage of correcting it as soon as possible and assuring the individual a healthy life. For this to happen, it is necessary that the baby wears a correction helmet so that, when it grows, its cranial box also grows mostly in the depression zones, making the curves more uniform (Villani & Meraviglia, 2014).

The correctional growth inside the orthosis is pictured in Figure 2.13.

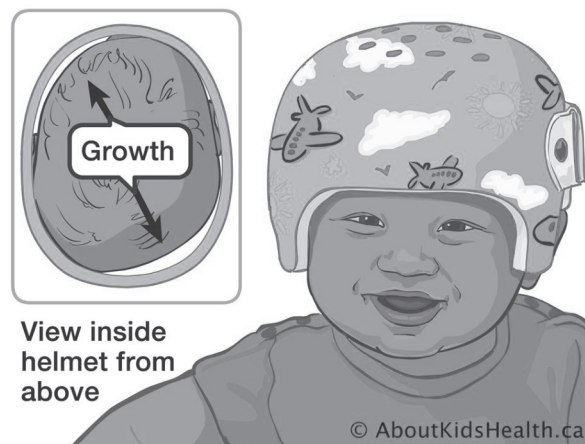


Figure 2.13. View inside of the correctional helmet (SickKids, 2020).

Towards the fabrication of this equipment, it was necessary to take a mould directly from the patient's head, which made the process very difficult since its young age, and it is challenging to place it static. Currently, the company "Padrão Ortopédico", like some other companies, uses 3D scanning technology, making it much easier to register the dimensions and shape of the head. Figure 2.14 shows the result of this procedure through an already machined mould that would be used as an important reference tool for the construction of the correction orthosis.

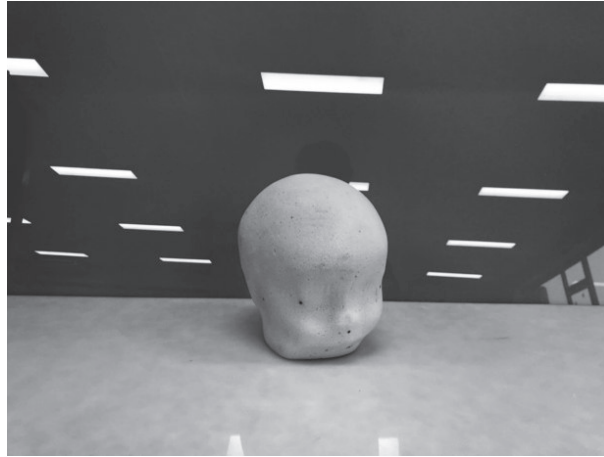


Figure 2.14. Foam replica mould of a baby head with plagiocephaly.

An example of the correction helmets manufactured by “Padrão Ortopédico” is shown in Figure 2.15 below, where it is possible to see its interior in ‘Plastazote’ foam wrapped in an outer layer of polypropylene.



Figure 2.15. Orthotic correction helmet produced by “Padrão Ortopédico”.

3 STUDY OF THE CNC FROM “PADRÃO ORTOPÉDICO”

For the growth of the projection on vacuum system it is necessary to know the best about the automatic machine. This includes its characteristics, as well as the identification of axes and work areas, to know its constituents well, post-processing activities and carry out a balance between strengths and weaknesses of the machining centre.

3.1 Examined Automatic Machine

To produce the orthotic helmets, it is needed at least 3 axes because of the geometry of the mould. It is used the revolution technique to tear the material around creating the perfect shape of the patient’s head. The parallelepiped shape of the CNC and verticality is due to the working area, also vertical, which enables the machine to further increase its versatility and produce moulds for complete legs. The Figure 3.1 represents the mentioned machine which has been analysed in its entirety.



Figure 3.1. CNC machine used for the production of moulds in “*Padrão Ortopédico*”.

For a better analysis of the mechanism an 3D model, using ‘Autodesk Inventor’, was made where all parts are represented with the corrected dimensions correspondingly to the real ones (Appendix I). This visual representation is shown in the Figure 3.2 below for the equipment structure as an all.

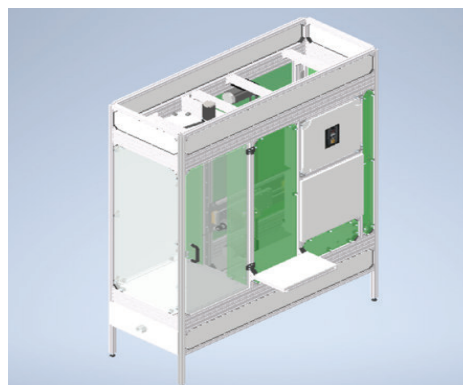


Figure 3.2. CNC machine designed entirely on ‘Autodesk Inventor’.

Hereupon the device is divided in the rotating plate named a, and the linear x and z axes, as it is possible to check on the Figure 3.3 below.

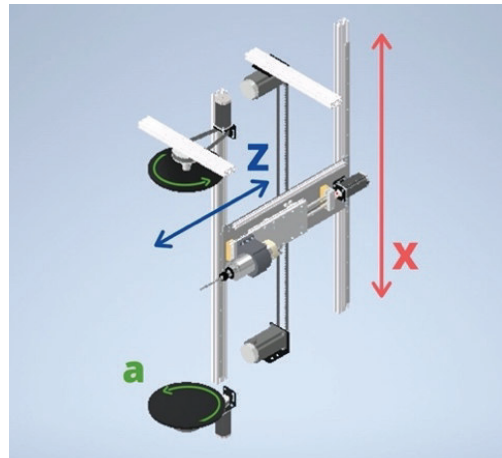


Figure 3.3. Working axes of the equipment.

The allocation of axes, as confusing as it may seem in this CNC in specific but following the 'right-hand rule', is easy to check this nomenclature given, including the absence of the y-axis. Figure 3.4 below is a representation of this.

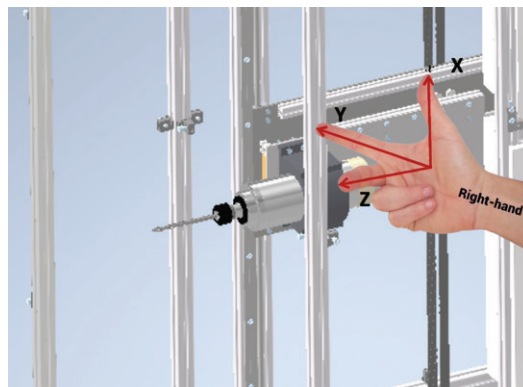


Figure 3.4. Application of the 'right-hand rule' to the machine.

The x-axis is defined by the centre of the tool table along the vertical slideways, with a total length of 1000 mm, corresponding to the maximum value.

Perpendicular to this and coincident with the centre of the tool, the z axis is described. This can extend from the tip of the tool, in the receding position of the ball screw guide, to its maximum position defined by the implemented limit switch, making a total of 500 mm.

Complementing the equipment's working axes are the rotating plates that increase versatility with the angular a-axes that allow to establish positions in a range from 0° to 360°.

These axes together give the possibility to machine biometric moulds in a working area with 260 e6 mm^3 of volume, shown in Figure 3.5 below.

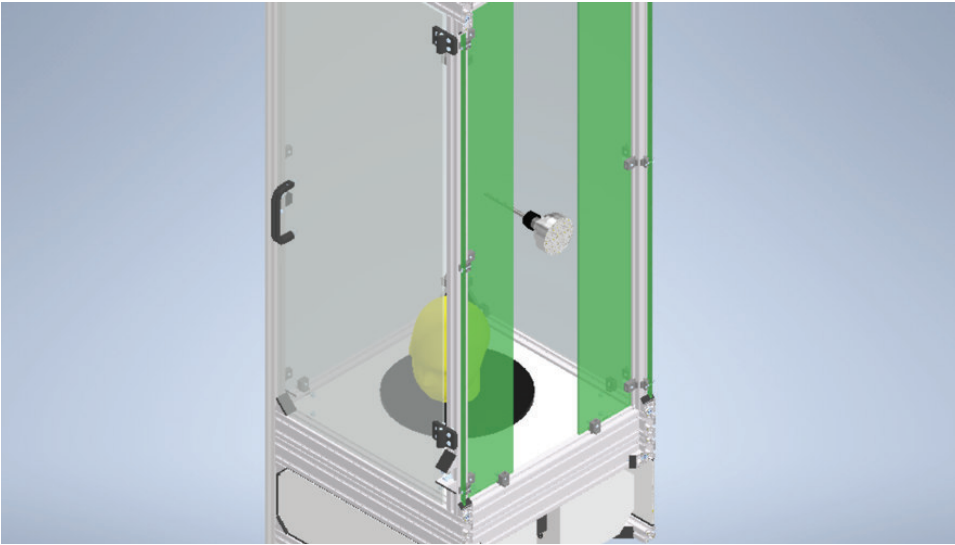


Figure 3.5. Working volume of the machine.

The automatic machine can also be divided into the transit area of the tool holder, the foam grain storage area and the electronic components area.

In the following Figure 3.6, an approximate view of the transit area of the tool holder with a total volume of 480 e6 mm^3 is shown.

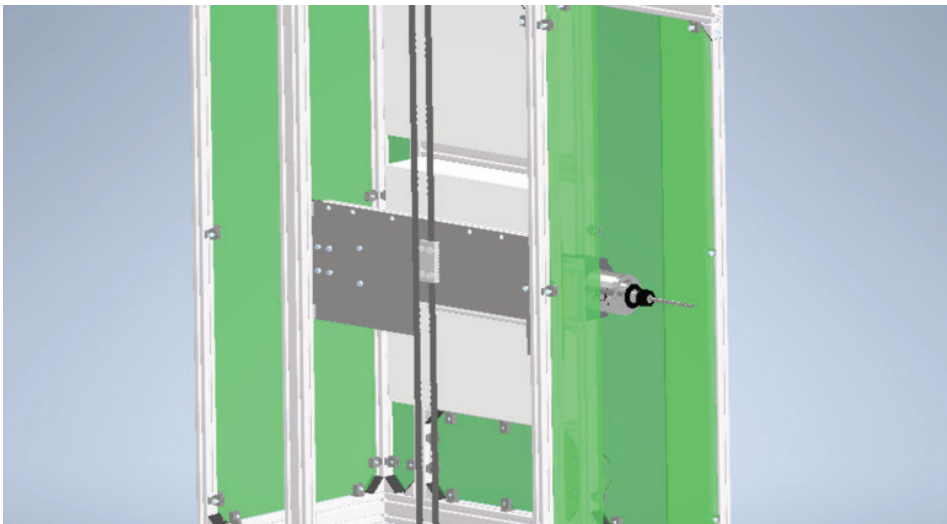


Figure 3.6. Movement volume of the machine tool holder.

The material used in the manufacture of moulds has a low density and by gravity the chipping of this material is deposited in a box with 20 e6 mm^3 of volume, as shown in Figure 3.7.

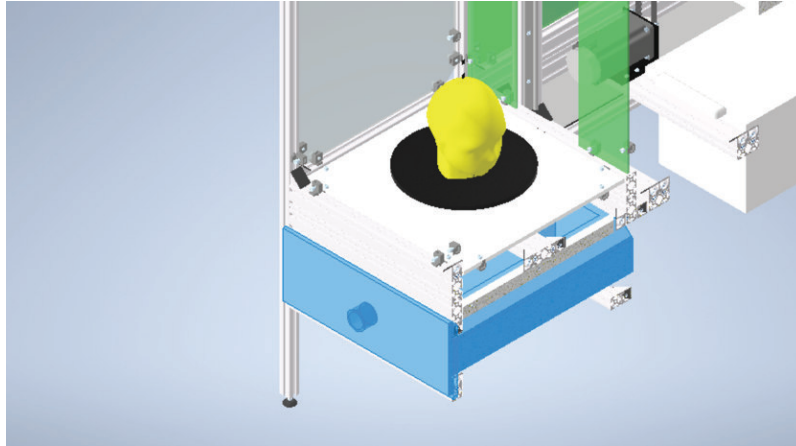


Figure 3.7. Volume of rubbish deposit resulting from production on the machine.

Attached to one side of the CNC is a container that defines the zone of the electronic components, or in other words, the area of control of the equipment. Figure 3.8 shows exactly that sector.

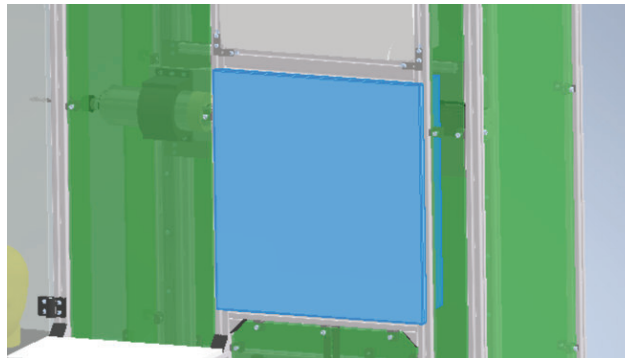


Figure 3.8. Volume containing the electrical part of the machine.

The electronic components were not designed and therefore as a real representation of the interior of this compartment is shown by the Figure 3.9 that follows.



Figure 3.9. Electrical and electronic components of the machine.

This is where all communication takes place from the sending of 'G-code' from the 'Arduino' controller to the engine terminals, making everything work in synchronization.

Due to its important role and in order to gather and organize information for future maintenance events, all connections that are difficult to view have been simplified, in a colour scheme that contains all the components of the network. Figure 3.10 contains this electronic scheme referred to.

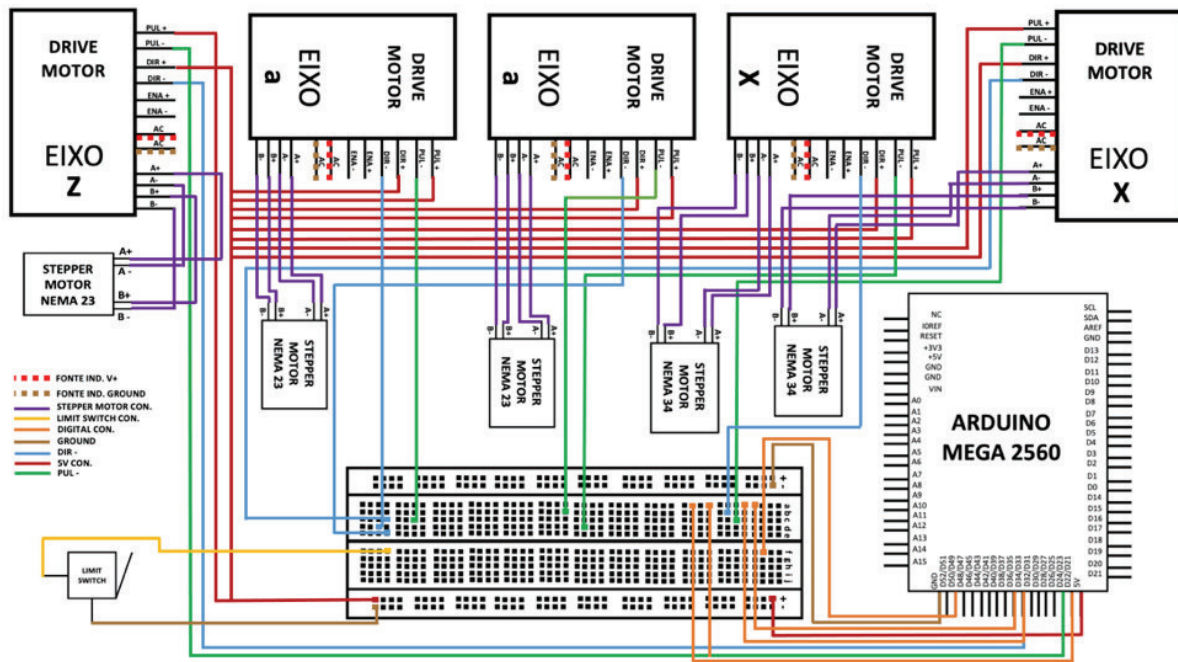


Figure 3.10. CNC machine general electrical circuit.

3.2 Equipment Components

A characteristic that is highlighted in this device is its visibility to the interior, due to the ten acrylic plates that cover a large area. This facilitates access to its interior to perform any maintenance or repair activity. This is easily verified by Figure 3.11.

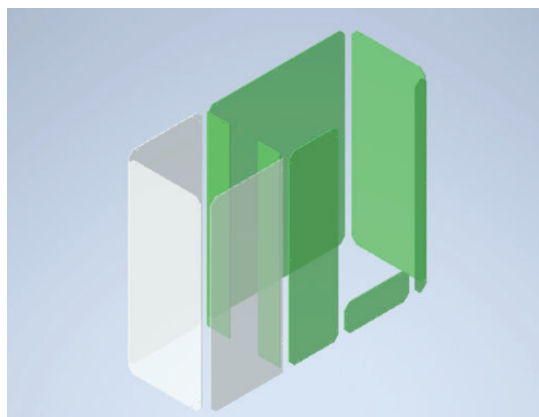


Figure 3.11. Acrylic separating walls.

The skeleton that supports all the weight of the constituent organs is composed of fifty-three anodised aluminium beams.

These profiles were produced by 'item Industrietechnik' and were selected due to their high load bearing characteristics and the resistance of the material.

In order to have a more accurate representation with the real one, the virtual 'item 24 engineeringtool' was used for the modelling of the initial structure.

In Figure 3.12 it is possible to see the supporting structure of the machine using two different types of profiles. Twenty-two units known as 'profile 6 30x30' and thirty-one called 'profile 6 60x30' are used, differing only in width.

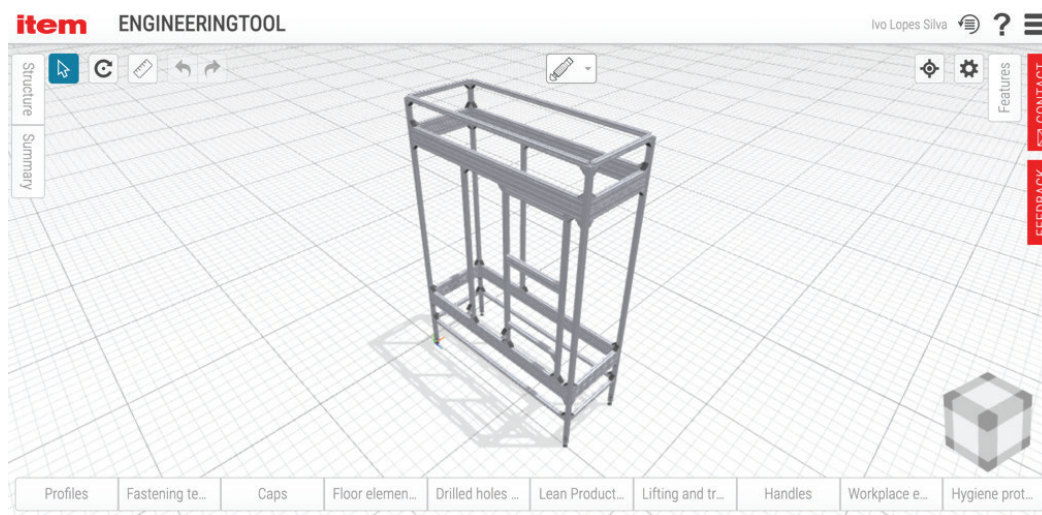


Figure 3.12. Automatic machine frame beams.




The following Figure 3.13 shows in detail the 30x60 and 60x30 profiles respectively.



Figure 3.13. Detailed view of the profile of the beams used (item Industrietechnik GmbH, 2020).

Responsible for fixing and connecting, similar to the role of the muscles, the structure includes the indispensable, brackets, fix blocks and also floor supports that allow optimal balance and structural consistence of the equipment. All these components are illustrated and quantified in Table 3.1.

Table 3.1. Quantity of auxiliary assembly components used

Bracket	Fix block + M5Ø	Floor support
		
92 Un.	78 Un.	4 Un.

In the same way that arteries are responsible for the transmission, through movement, throughout the system, guides and pulleys are responsible for this task in the automatic machine.

Although the machine operates on only three axes (two linear and one rotary), six pulleys, two drive belts and a ball screw are used, to make optimal movement possible during tool operation.

Regarding the y-axis, vertical linear movement of the tool, it is formed by a toothed belt of length 260 mm and two pulleys, with fourteen teeth each, placed by tightening to two parallel motor shafts. This transmission system is shown in Figure 3.14.

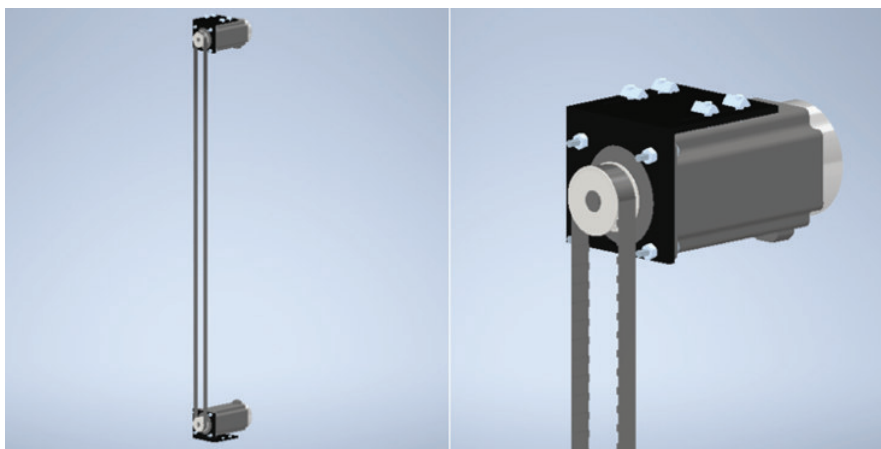


Figure 3.14. Components of the y-axis and approximate view.

The rotation axis, composed of the rotating plate where the raw material to be machined is fixed, is divided into two systems working simultaneously.

The workpiece can be embedded either at the top or at the bottom in the tool working area. Both sides have a swivel mechanism consisting of a toothed pulley, customised with a slotted cylinder attached to the profile 6 60 x 30. Embedded in this pulley with thirty-four teeth is, by tension, a toothed belt of length 65 mm which joins it to another pulley, with fourteen teeth, secure to a motor shaft as represent in Figure 3.15.

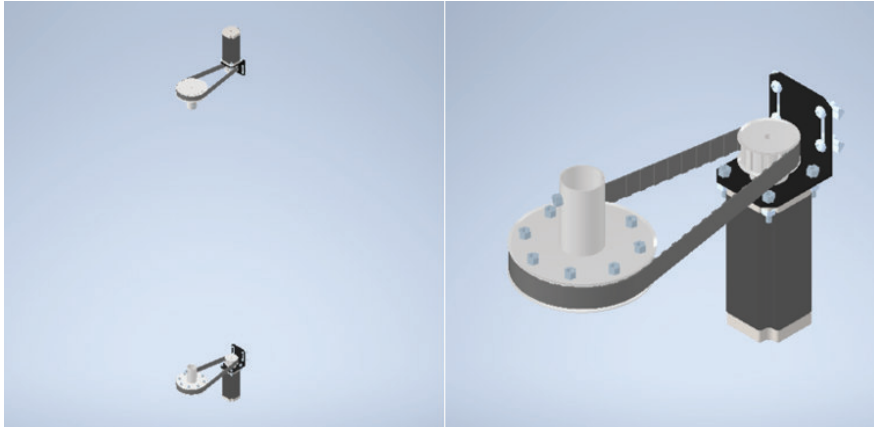


Figure 3.15. Components of the rotary axes and approximate view.

The axis which is most responsible for the thinning out of material, so as to be more sensitive during its movement, was used by a different type of transmission from the previous ones. This z-axis, imaginatively planned for the length of the tool, is carried out by a motion transmission mechanism, a ball screw and four guides, of which two are movable and two are fixed. The movable ones offer the spindle the forward and backward movement of the tool, these and the rest of the axis system being illustrated in Figure 3.16.

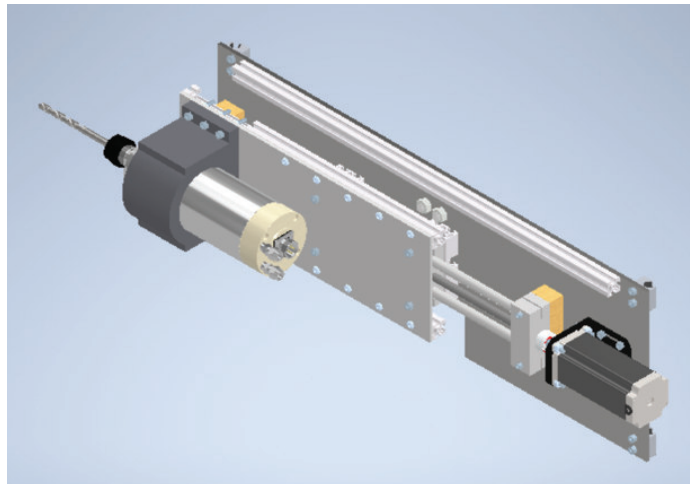


Figure 3.16. Components of the z-axis.

As the brain of the whole machining operation, the electrical installation is subdivided into motor drivers and a mega 'Arduino' for the process and control of the 'G-code' sending, which is currently connected to an LCD 'Raspberry Pi' display which offers a customised control specifically for the machine of which it is part. This controller and display were developed in parallel by trainee Francisca Vigo.

Just above the breakdown where this electrical and electronic connection and communication is located, a manual spindle controller is present, thus avoiding more unlucky events and facilitating the response in the event of their occurrence.

Both communication and control areas mentioned are protected by the reservoirs shown in Figure 3.17.



Figure 3.17. Communication and control compartments.

By centralizing all the action at its fingertips is what a human hand and the spindle of the equipment have in common. This part is manually controlled in the volume represented above and has a water-cooling system, by connection to a tank. This ensures that there is no overheating of the tool when reaching rotation values of 24000 rpm. Figure 3.18 represents the mentioned spindle and its $\varnothing 8$ mm drill (Tomschi, 2020).



Figure 3.18. Standard Chinese spindle and twist drill.

Last but not least, like any living organism, the heart that pumps the transmission chains is needed, in this case shared by five 'NEMA' engines. The 'NEMA' engines used were of two models, 'NEMA' type 23 and 'NEMA' type 34.

'NEMA' 34 has higher torque, can reach 7.07 Nm, and uses higher feed rates, which makes it possible to transport the tool holder vertically with its high weight. The two motors of this type are shown together with the tool holder in Figure 3.19.

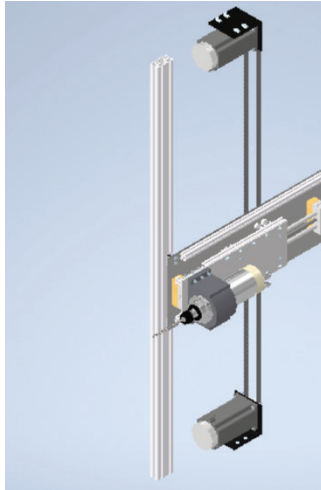


Figure 3.19. Linear tool holder sliding system using 'NEMA' 34 motors.

The 'NEMA' 23 engines cannot be underestimated, with their high torque of 3 Nm, as they are ideal for performing different tasks. Two motors of this type are used on the lower and upper rotating plates of the machine, where their performance allows to control the exact angle of rotation and direction of rotation of the block around its axis. The following Figure 3.20 shows the position of the engines at different mooring locations.

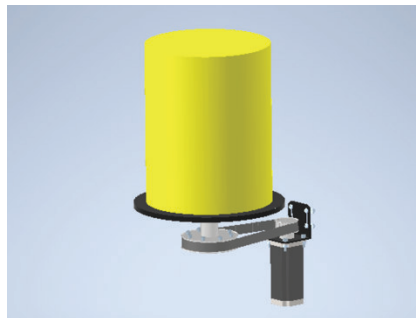


Figure 3.20. Rotating plate using 'NEMA' 23 motor and mould block.

The third 'NEMA' 23 motor is located on the spindle mooring plate and is responsible for its advance and recoil. The motor transmits its torque by coupling with a ball screw that advances the tool's slide guides as shown in Figure 3.21.

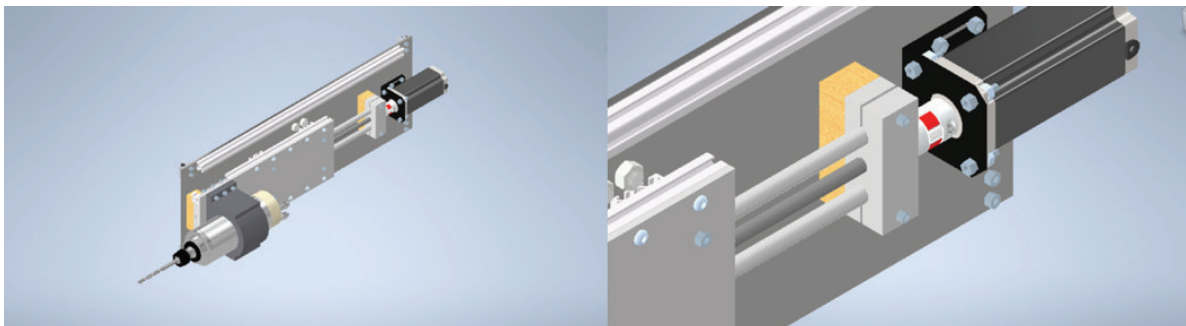


Figure 3.21. Feed drive connection of the toolholder table and approximate view.

3.3 Equipment Post-Processing

For the purpose of a better interpretation of the developed project, all the steps necessary before the machine's working procedure are explained in this section.

The first step is to transfer real data into virtual data using a 3D scanner as shown in Figure 3.22.



Figure 3.22. Scanning baby's head with 'EinScan-Pro+'.

For a better accuracy of the dimensions to be treated, the 'EinScanPro' software helps the user to know which regions need special attention for a better conversion to the CAD model, as shown in Figure 3.23.

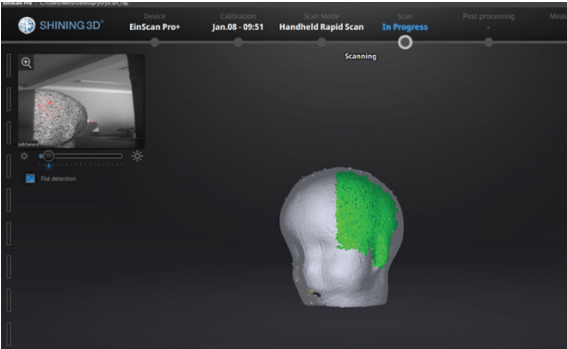


Figure 3.23. Three- dimensional scanning process in 'EinScanPro'.

As a result of the 3D scan the STL file is treated and adjusted, with expert insight into the critical points, to ensure greater accuracy in the mould printing.

Figure 3.24 shows, with the assistance of 'Autodesk Meshmixer' software, a model of a baby's head with plagiocephaly.

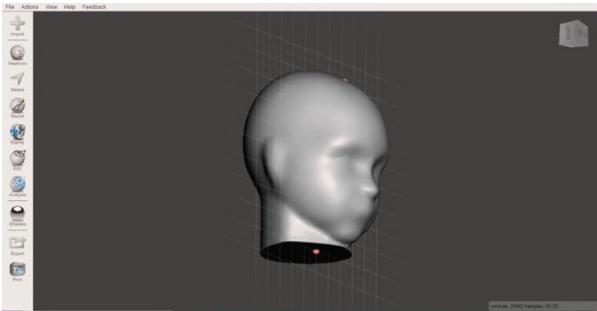


Figure 3.24. Treatment of the CAD model in Meshmixer.

This software gives access to the user, who with a sensitive knowledge of the important measures to be transposed into the mould, to grind and check the CAD model before the machining process.

By way of the CNC only operates vertically, the recommended software for translating a CAD model for 'G-code' commands is 'Deskproto'. This allows to predict the machining process before it happens and to adjust the tool path in the most cost-effective and fast way possible.

In the following Figure 3.25, it is possible to visualize the simulated trajectory of the tool already in the final phase of analysis, ready to export the result to 'G-code'.

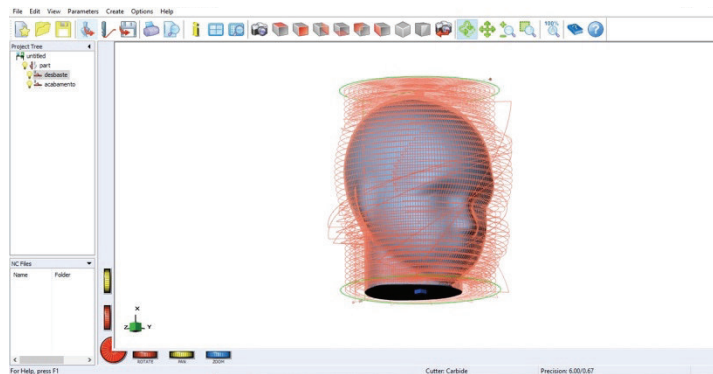


Figure 3.25. 'Deskproto' CAD model treatment.

As a result of the above process, a text file is obtained with a sequence of letters and numbers, defined by 'G-code', as shown in Figure 3.26 next.

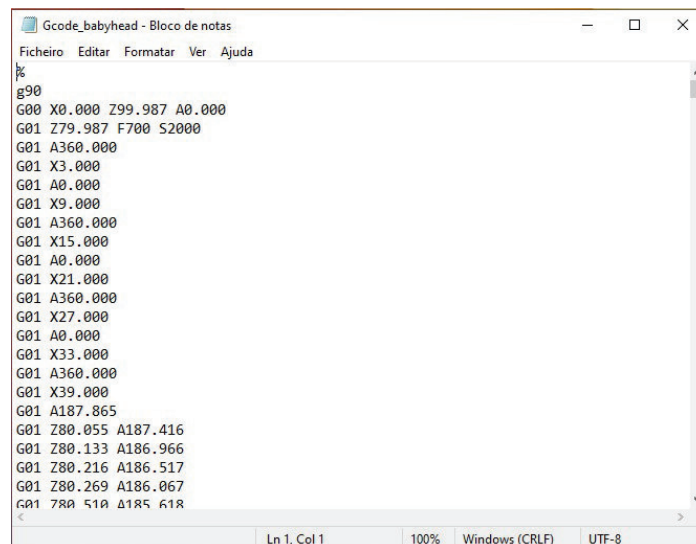


Figure 3.26. 'G-code' commands in notepad.

Now that the shape of the patient's head is translated into an interpretable language by the CNC machine, it is necessary to send it to the equipment.

Before this is done, the entire code tracking is analysed using the 'GRBL Controller', as shown in Figure 3.27 below.

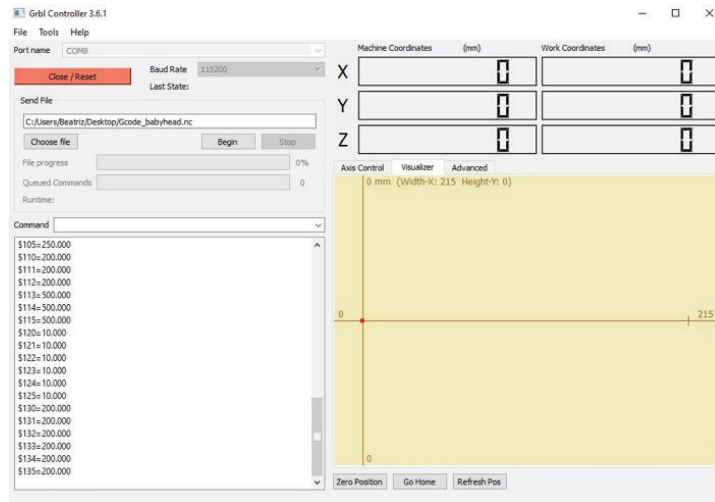


Figure 3.27. Analysis and handling of 'G-code' commands using the 'GRBL controller'.

The controller that operates the motors so that they work synchronously, is a 'Mega Arduino 2560' that has been represented in the circuit of the electrical components of the machine before. In this micro controller is inserted the 5/6 Axis version of 'GRBL', the open source, embedded, high performance 'G-code'-parser and CNC milling controller written in optimized C (Brière, 2020). Responsible for the command flow, being the final step in the post-processing of biometric mould production. The logo of this firmware is shown in Figure 3.28 following.



Figure 3.28. 'GRBL - Mega - 5X' logo (Brière, 2020).

In addition to these post-procedures for transmitting the desired part design to the machine, it is necessary to manufacture the blank mould. The material of this raw block consists of a mixture of two liquids, one responsible for the filling and the other for its hardening. A quantity of 600 ml of each is used and its containers are shown in Figure 3.29.



Figure 3.29. Liquid containers used in the production of the foam mould and its hardener.

As it is possible to see in Figure 3.30, these reagents are mixed with the help of a drill with blades until the combination is homogeneous.



Figure 3.30. Mixture of the reagents for the production of the foam mould.

At the end of this previous step, before pouring all the fluid into the mould container, a plastic bag is placed inside the negative mould in order to protect it and avoid a chemical reaction, as the material is PLA. Both the parts that constitute the shape of the primary mould block and the process of its filling are shown in the following Figure 3.31.



Figure 3.31. Leakage of the mixture into the container resulting in the mould block.

After a minimum of one hour of solidification the block is ready to be extracted from the container that gave it shape. As it is assembled with the aid of bolts which make its tightness ideal for there to be no leaks, all necessary to do is loosen them and carefully remove the block, also removing the plastic bag. The result of this process is shown in Figure 3.32 below.

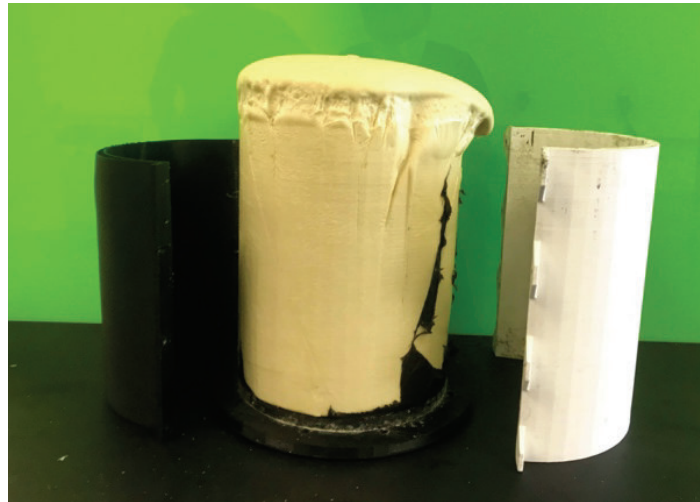


Figure 3.32. Raw block ready to machine after hardening and separation from its mould.

In order for the tool to work little time and to make the roughing process as profitable as possible, the geometry of the block is milled with an industrial sandpaper. Represented in Figure 3.33.



Figure 3.33. Grinding of the block geometry with an industrial sandpaper.

The block dimensions are corrected until it is 200 mm in diameter and 300 mm high.

After the correct fitting of the primary block to the rotating plate is ready to be machined. Thus, completing the necessary processes prior to the operation of the automatic equipment.

3.4 Problems Acknowledged

The equipment studied functionality is totally suitable for the manufacture of the orthosis mould. However, the company that uses it would like to increase its usefulness for working with an additional axis in order to produce more products, such as orthoses insoles, that are fabricated hand made by “Padrão Ortopédico”.

A foam mouldable to the bottom and side of the foot is used for corrective gauging of the geometry of the entire sole of the foot. This foam is represented in Figure 3.34.



Figure 3.34. Mouldable foam to dimension the shape of the foot.

The cavity formed in the foam is filled with a compact plaster paste which, after a drying process, is used as a positive mould in reference to the manual manufacture of an insole. The following Figure 3.35 shows a plaster cast similar to the patient's foot, and an insole already in the final production process.



Figure 3.35. Replica of the foot in a plaster cast and its insole made.

Because the reference mould has a very complex geometry with specific concavities, it is not possible to machine it very precisely because it would not replicate the dimensions and shapes corresponding to the real ones. This is the reason why the CNC machine studied is not able to produce this type of mould for

orthoses. However, it is the process adopted by other companies as it is represented in the following Figure 3.36, made by 'London Orthotics'.



Figure 3.36. Insoles machined by 'London Orthotics' (London Orthotic Consultancy, 2020).

The geometry of the insoles mould would require an extra horizontal axis, perpendicular to the operator, defined as the y axis.

After an extended analysis on the cost, work and time needed for adding this working axis, it was determined that would be more efficient to build an extra CNC only for the production of the insoles. Thus, a problem that was solved with the architecture of a future project to be developed in this equipment.

Other problems detected on the CNC is the visual interface and vacuum system of foam's chip, resulting from machining.

When it comes from the visual interface, the problem was perfectly solved parallel to this dissertation by the intern of the company Francisca Vigo.

Vacuuming the foam left by the machinery procedure was primarily done using a technique represented below on Figure 3.37.

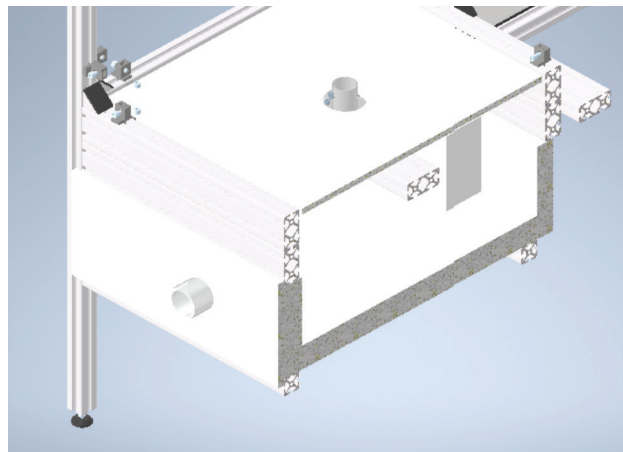


Figure 3.37. Section view of the chip aspiration and collection cavity.

On the bottom part of the working space, there is a container responsible for the collection of the foam's chip and on one of its face a hole where the conventional vacuum cleaner's tube would be inserted for the aspiration.

This method is not the most practical because of the density and weight of the chip. It's electrostatic makes it stick to the inside of the machine, in and out the working space, resulting in a more difficult way to get rid of it, as shown in Figure 3.38 below.

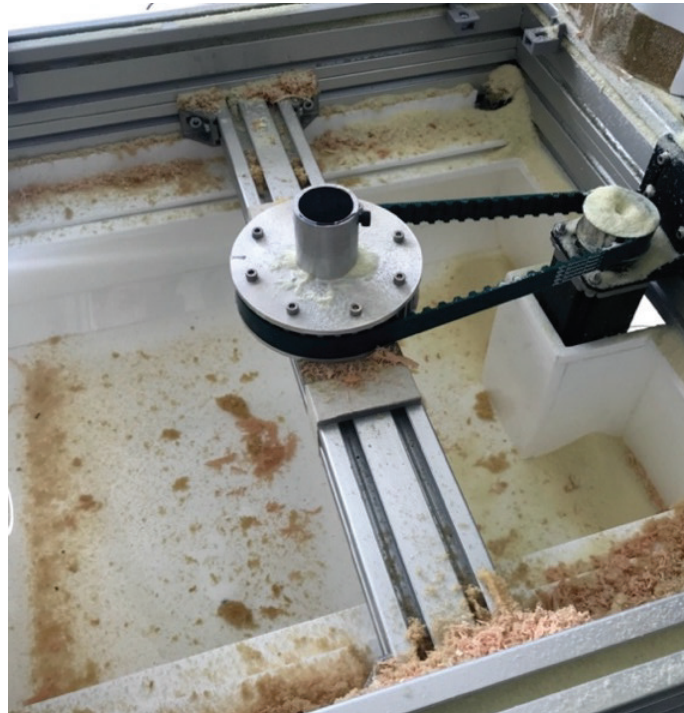


Figure 3.38. Rubbish found in machine cavities from foam chipping.

In addition to being a problem that makes the machining place not visually appealing, the motors, belts and pulleys are affected by the foam accumulated in their bowels, which can even cause the motor shafts to become jammed or stopped.

In order to characterize the material of the chip removed as that of the mould produced, several descriptive terms and numerical parameters can be used particularly for granular bulk solids. These aspects refer to the appearance and behaviour of the material.

As the foam specifications are not fully standardised because it is a solution resulting from mixing, it is initially necessary to establish its behaviour feature based in Table 3.2.

Table 3.2. The 'Materials Personality Test' (Woodcock & Mason, 1987)

<p>Neurotic materials have poor flowability have too much flowability are sticky or tacky or tend to pack or bridge</p>	<p>they move awkwardly</p>
<p>Sadistic materials are abrasive, corrosive, toxic, explosive or hot</p>	<p>they attack their surroundings</p>
<p>Masochistic materials are friable, degradable or contaminable</p>	<p>they suffer from their surroundings</p>
<p>Schizophrenic materials are hygroscopic or susceptible to electrostatic charge</p>	<p>they change their behaviour pattern</p>

The type of foam can be analysed and treated as a neurotic material as its solid grains have plenty of flowability and moves awkwardly, sticking at the nearby entrances. Accumulated foam dust is compressed into cavities whose applied tension can be of great magnitude as illustrated in Figure 3.39 below.

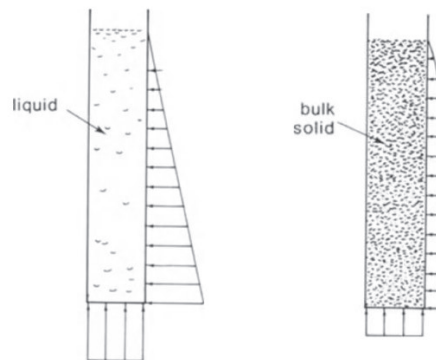


Figure 3.39. Pressure distributions due to weight alone (Woodcock & Mason, 1987).

Consequently, this struggle led to the development of a project for its resolution.

4 PROJECT AND CONCEPTION OF A DUST SUCTION SYSTEM FOR THE CNC MACHINE

This chapter includes the different stages of the process of projection and creation of the suction system designed as a useful and necessary cleaning solution for the machine.

Next steps follow an order similar to the topics included in the v-model of design methodology for mechatronic systems. Initially a survey is made of requirements that has to be quite present not only at this initial stage but also during the whole process of equipment construction. This step is termed elicitation requirements.

The next stage includes the selection of the model and suction technology as well as the electrical components to be used. This point called 'architecture and design' also has the help of software that allows the creation of CAD models in three dimensions to shape the parts that would form the suction equipment. Then it is also verified that all the dimensions and shape of the parts created meet the criteria.

The process of simulating the behaviour of the designed parts is fundamental to give the green light to the start of their production. This is why this section includes the simulations performed and their results. As the name of this stage indicates, the elements of the system are implemented.

In sequence, the parts are produced correctly, and the entire suction system is integrated and checked in the CNC machine, including both electrical and mechanical parts. That is the reason this process is called system integration and verification.

Finally, in the last section of the chapter a conclusion based on important points of the project is presented, thus making its validation and transition.

4.1 Requirements Elicitation

The primary state of the project development process was to list the requirements that the system to be integrated would have to meet. This should give the CNC machine organs a longer life span and longer intervals between maintenance periods.

In order to solve the recognised problem for the vacuum system of the automatic machine, an investigation was carried out into the best place where the Hoover should be installed.

It is really problematic that all the solid is deposited inside the deposit box, not only because of its low grain density but also because of the diameter of the particles, which makes it more likely to be lifted by the air flow and spread everywhere, polluting all the cavities of the equipment. This event forces maintenance to be done more periodically than it should be.

Originally, foam thinning occurs where the tool meets the block of material, which is considered the best place for the vacuum to occur without letting the particles escape. This area where the particles come out projected in greater quantity is highlighted in Figure 4.1.

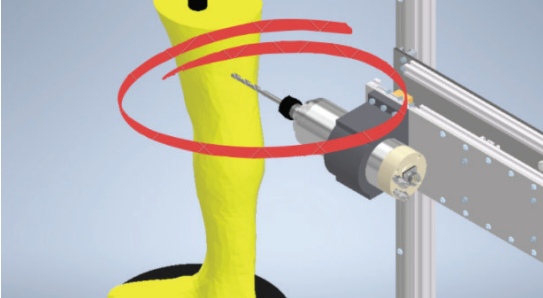


Figure 4.1. Best suction area for foam particles.

As far as the unused volume inside the machine tool frame is concerned, there is only one place where is conceivable to place the suction system so as to have close access to the suction area, not disturbing the tool holder's trajectory area. This most ideal free zone is represented in Figure 4.2 below.

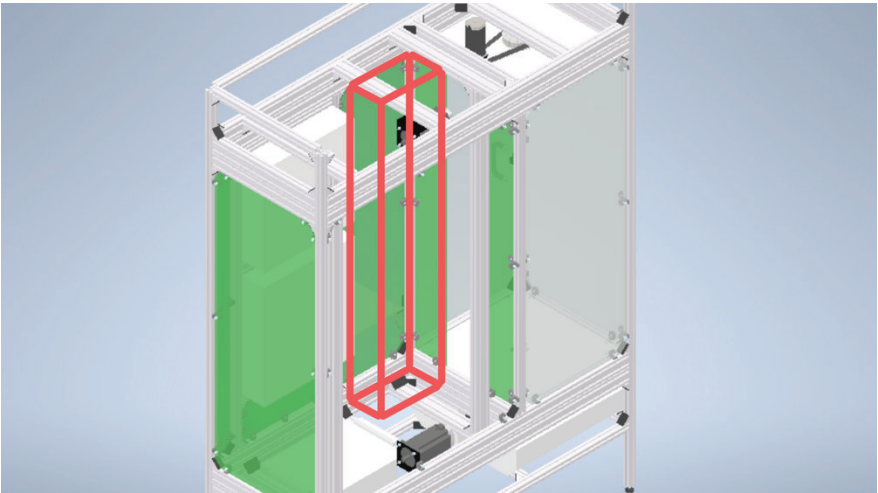


Figure 4.2. Free area inside the machine.

In addition to the suction system having to suck in an area near the end of the tool and being inserted in the studied machine, in a reduced volume without interfering with the other components, another requirement has to be met. This requirement consists of allowing the user to carry out maintenance of the Hoover, change the bin and switch the device on and off without having to remove the parallel acrylic wall closest to the tool holder.

In order to ensure that no functionality requirements of the suction system are not forgotten during the development of the project, this entire list has been assembled in flowchart form represented by Figure 4.3.

General Functions of the Suction System

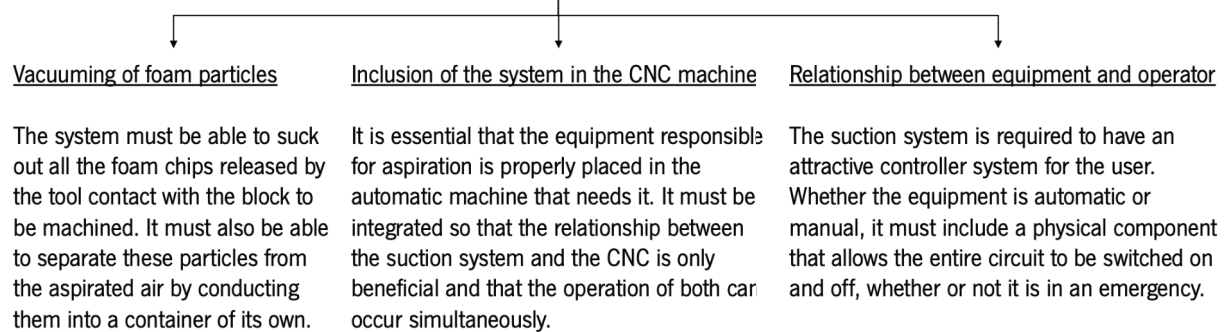


Figure 4.3. General functions of the suction system diagram.

4.2 System Architecture and Design

Architecture and design is one of the most pivotal periods in the development of a mechatronic project. It is at this stage that the project begins to take shape.

Although it is always possible to draw inspiration from models with existing geometries, it is necessary to create a design and architecture totally specific to the intended task.

In this chapter it is explained how the ideal suction model was achieved, the process of designing the mechanical parts, selecting the most suitable engine for the system and a final assembly that is essential to verify that the relationship between the parts of the equipment is stable and reliable.

4.2.1 Suction Model Configuration

For the architecture and design of the vacuum system different models of centrifugal collectors were studied in order to choose the most suitable design for the project. This type of collectors is used for suctioning a gas, in this case air, and separating the dust it may contain.

As this is a vacuum system of the suction type and not a blower, it follows the same flow technique as conventional hoovers. This consists of containing a suction opening, which would be the gas inlet to a low-pressure zone formed with the aid of a turbine.

In order to know what type of hoover and what technology to use, it is advisable to study the previous integrated system and based on its strengths and weaknesses, define the type of model desired.

By analysing the suction system that was already attached to the machining centre it is possible to classify the mechanism as too complex for this purpose and not practicable. The design of the hoover used is

exactly the same as any other conventional model that most people have in their home. This device is low cost and is a good choice when it comes to vacuuming dust located at the inlet end of the pipe. However, its exaggerated dimensions do not make it a viable model to follow.

Another negative aspect to perform the specific task is its suction technology. The aspirated air passes through the tube and is concentrated in an inner cavity of the Hoover. In this cavity the air containing dust particles is sucked in by a turbine which expels only the air. The particles, according to their size, get trapped or fall by the effect of the dust filter.

The use of a dust filter in this specific case is completely to be avoided since the necessary hours of operation and amount of material sucked in are much higher than the normal values that the abolished equipment demonstrates. Figure 4.4 below explains the operation of a conventional two-stage Hoover.

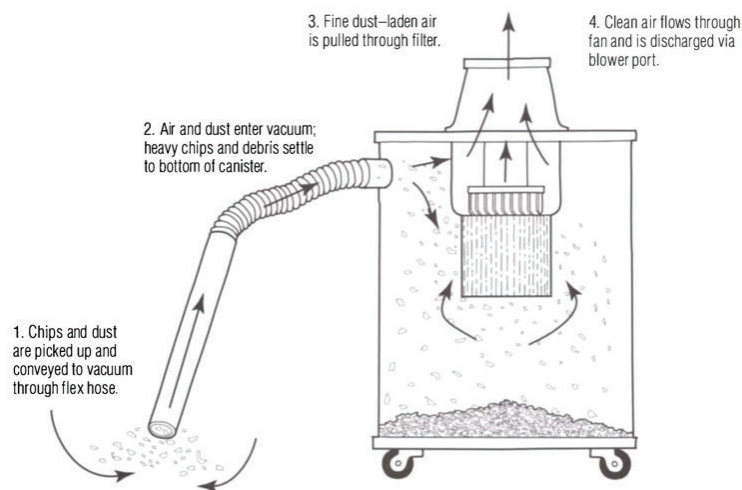


Figure 4.4. Two-stage shop vacuum cleaner (Nagyszalanczy, 2002).

The suctioned material is a very small grain diameter foam and in addition to static adhesion to surfaces, it can also block cavities. Given these characteristics, the suction system must use some technology to separate this dust contained in the air without direct filtration.

A suction equipment capable of separating particles contained in the air without the use of a filter is called, according to its function, dust collector. These can be single or multi-stage depending on the intention to separate only one or several types of dust from the vacuumed air. In this case it is only important to separate one type of dust.

There is an anatomy of centrifugal suction pumps which is the cyclone. These dust collectors are efficient in collecting and separating dust contained in the sucked gas.

Also, with similar technology to conventional hoovers, cyclone collectors have an inlet through which all the air is pulled into a depressurized area that when the turbine ends its operation, or even during it by gravity, all the waste that was in the air falls. This now clean air is sucked in by the same turbine in action, which is an impeller. It is then sent out through an outlet to the outside environment. The mentioned system is represented illustratively in Figure 4.5 below.

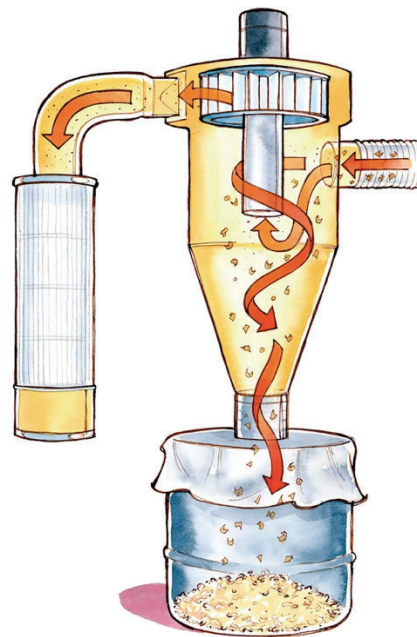


Figure 4.5. Gas transit within a suction model with a cyclone system (Christiana, 2012).

After intensive research on the strengths and weaknesses of this type of dust collector, one of the most discouraging information found was that it is not advisable to build a dust-collection cyclone because the construction and connection is somewhat complex due to its metal parts.

However, this point is easily refuted because due to current technologies and also available in “Padrão Ortopédico”, it is possible to print its constituent parts on a type of polymer, called PLA, through 3D printers.

Considering then that the cyclone model is the most competent one to fulfil the needs, it is necessary that it fulfils the correct dimensioning.

According to a study on how to determinate the best dimensions so that the cyclones perform the best possible performance, it was possible to find a table that gathers all the dimensional ratios between the different dimensions of the anatomy of the Hoover body. This table and its illustration of the meaning of the dimensions are shown in Figure 4.6 that follows.

	Cyclone Type					
	High Efficiency		Conventional		High Throughput	
	(1)	(2)	(3)	(4)	(5)	(6)
Body Diameter, D/D	1.0	1.0	1.0	1.0	1.0	1.0
Height of Inlet, H/D	0.5	0.44	0.5	0.5	0.75	0.8
Width of Inlet, W/D	0.2	0.21	0.25	0.25	0.375	0.35
Diameter of Gas Exit, D_e/D	0.5	0.4	0.5	0.5	0.75	0.75
Length of Vortex Finder, S/D	0.5	0.5	0.625	0.6	0.875	0.85
Length of Body, L_b/D	1.5	1.4	2.0	1.75	1.5	1.7
Length of Cone, L_c/D	2.5	2.5	2.0	2.0	2.5	2.0
Diameter of Dust Outlet, D_d/D	0.375	0.4	0.25	0.4	0.375	0.4

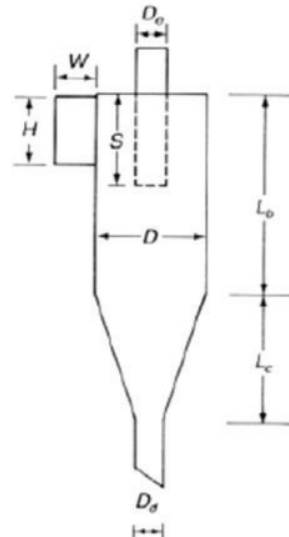


Figure 4.6. Ratio of hoover geometry dimensions in cyclone hoover (Bashir, 2015).

Now with insight into the relationships between the dimensions of a high efficiency standard cyclone type 1 it is possible to start the design of the project. The first model was selected because it presents a ratio of values closer to the units, which in this designing is beneficial since certain dimensions and relationships between them had to be changed.

However, although it is possible to support the design dimensions in the information found, it is always necessary to adapt the geometry with vision to the specific problem of aspiration of the CNC machine. In this way, the suction hole for the interior of the aspirator is designed in a circular shape, maintaining the sizing area of the air intake for better performance and layout. The exit orifice is also designed on the lateral side of the aspirator body and not on the top, also keeping the sizing area according to a rectangular section similar in height to that of the turbine.

4.2.2 Development of Mechanical Parts

Once it's recognized the recommended relationship between the dimensions of the cyclone type hoover together with the necessary changes to the specific function it would perform, it is possible to design the constituent parts. All the design of the vacuuming system was carried out with the support of 'Autodesk Inventor' software, thus allowing the creation and preparation of parts and their assembly in CAD (Appendix II).

The design began with the body where air circulation and separation by gravity of the foam particles occurs. As this part of the system contains almost the entire flow region, it should be completely sealed and should not leak anywhere. Its cylindrical and conical shape, with appropriate dimensions, helps in the air circulation process. The part mentioned is shown in Figure 4.7.



Figure 4.7. Suction system body part.

As the inlet and outlet geometries of the suction system have been changed, it is necessary to confirm that all arbitrary dimensions respect the studied dimensioning ratios. This has been complied with measures close to diameter, height and air intake area in the body.

A new component has been designed with a geometry suitable for coupling to the body of the suction system. This part attends to support the engine to be introduced, and inside it contains the rotation zone where the impeller turbine would be inserted, thus creating different pressure and suction points at the entrance of the body, represented in Figure 4.8.



Figure 4.8. Suction system motor support part.

This upper casing of the suction system also has an air outlet necessary for the gas to escape without particulates included. The outlet on the side of the new part's cylinder, despite being rectangular to follow the trajectory of air leaving the turbine, has dimensions whose area is similar to the standard area given by the gas outlet diameter.

External holes were also drilled to coincide with them on the edge of the upper body so that they fit perfectly and no gas escapes. In order to guarantee this tightness, a coupling sleeve was designed to be positioned between the two parts, which was later reproved for its use, because without it a better sealing

of the system is achieved. However, this accessory part not used in the final assembly is shown in Figure 4.9 below.

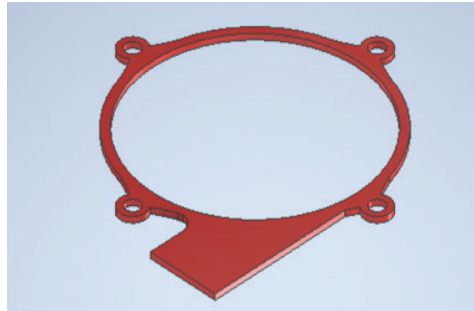


Figure 4.9. Suction system gasket part.

For the design of the turbine, some important requirements emerged in the arbitrage of its dimensions and geometry. The turbine must have a geometry so that the entire volume of the piece can drag as much air through its blades as possible.

The design of the turbine blades is the most important part as it would influence the performance of the air circulation within the suction system. Based on the different types of impellers and the use of each for different situations required, it is possible to choose an ideal model for the case under study. The number of blades selected is six equally spaced blades, with a certain curvature and side cut. The design of this geometry took into consideration the aerodynamic behaviour performed by the turbine so that aspiration is possible in its entirety.

With regard to the turbine mooring to the engine it was considered that it should facilitate the maintenance process of the designed device and also be possible to replace the turbine by other models to test its efficiency. For the same reasons a direct connection of the engine shaft to the turbine face was determined. In order to ensure that the engine shaft is always aligned with the central cavity of the turbine, two holes were also made on the sides of the central cylinder of the turbine which, with the help of two screws, prevents the motor shaft from slipping inside the turbine. The model designed based on the needs described is shown in Figure 4.10 below.

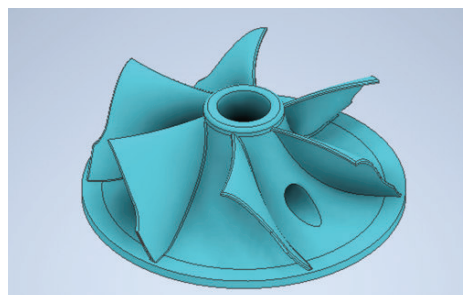


Figure 4.10. Suction system turbine 0.5 part.

Although the parts that have been drawn may appear to be sufficient components for the construction of the cleaning system of the CNC machine, they are not. The method of attaching them to the machining centre remains to be defined and planned.

As previously shown the volume available inside the machine tool, a plate has been designed with the function of mobilizing the Hoover in this volume. Although this support plate has a somewhat simplified geometry, it contains specific dimensions which have been studied and compared to the actual measurements of the CNC machine. Its length must coincide with the distance between the beams at the top of the automatic equipment and the hole inside it with a diameter with a suitable tolerance for the perfect fitting of the suction device body in order to keep it immobile and well supported without applying great tension. The following Figure 4.11 illustrates the mentioned drawing in three dimensions.

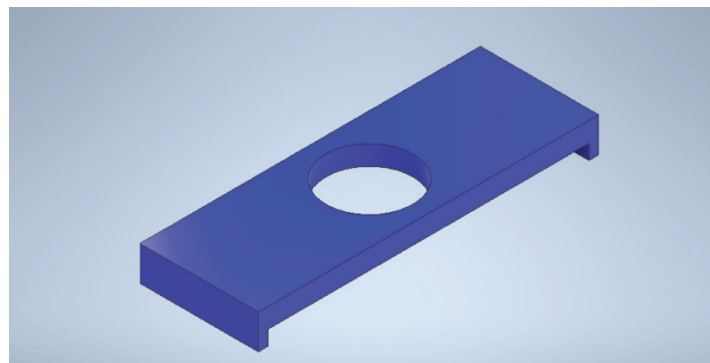


Figure 4.11. Suction system plate part.

In the same way as every light fixture needs a bulb, a Hoover is also not complete without a tube. The suction tube to be included was removed from a conventional Hoover. The dimensions of this one are totally pleasant for the fitting of its extremity with the entrance hole of the cleaning system of the CNC machine.

The tube with a length of 1.50 m is suitable for the minimum size it would need if the suction equipment is to be affixed to the top of the free area of the automatic machine to the tip of the tool at its lowest level. The outer diameter of the tube is perfectly suited for an optimum fit to the inner diameter of the air intake, with suitable tolerance values range.

The architecture of the suction pipe has to be more complex. Auxiliary parts had to be designed to ensure that it is always attached to the spindle and that it vacuums according to an area suitable for the indicated suction area. These parts have been designed with tolerances appropriate to the outer and inner diameters of the pipe for the connection or support of the tubing. The part responsible for joining the pipe to the spindle of the machine is shown in Figure 4.12.

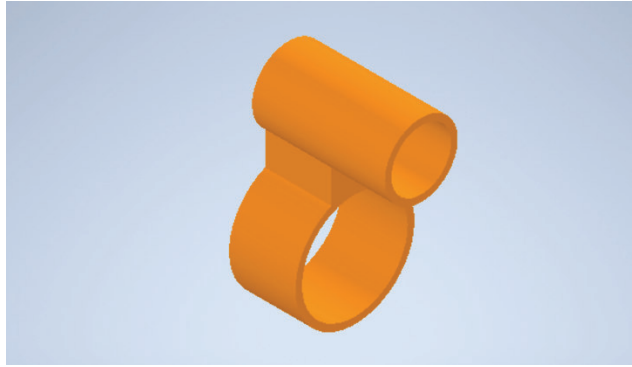


Figure 4.12. Suction system tube holder part.

Once the part that holds the pipe has been designed, it is necessary to complement it with another piece that gives it a wider opening area. The geometry of this part must also contribute to the air intake in the suction system being always parallel to the tool and in front plane with the suction area, for a more efficient suction. The part designed for this function is shown in Figure 4.13.

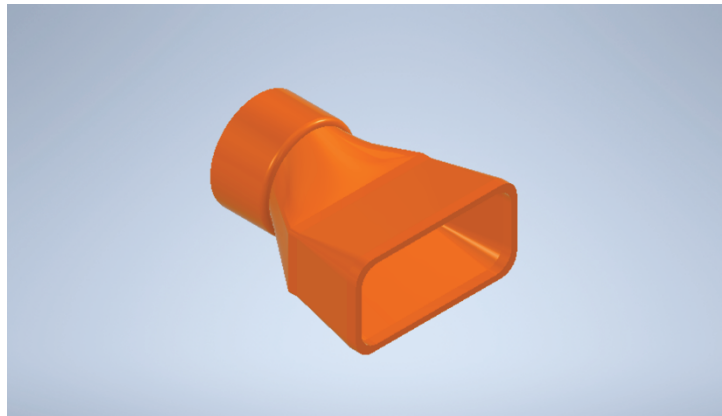


Figure 4.13. Suction system tube adaptor part.

With the addition of this new auxiliary part, the suction area is now $84 \times 39 \text{ mm} = 3276 \text{ mm}^2$. All the parts now totally designed and architected it is possible to proceed to the next essential step in the projection and elaboration of a mechatronic project.

4.2.3 Selection of Electric Motor

The essential holes in the central area of motor support component illustrated in Figure 4.8, are used to affix the engine directly to the suction system and the respective turbine that would be inserted inside it. In order for these holes from the motor support and the distance between them to coincide with the dimensions of the fixing holes present in the engine, it is necessary to make the correct selection of the engine.

The desired engine has to meet a selection of requirements. It is intended that this engine is directly coupled to the turbine, thus being a low load object. The engine being attached to the top of the motor support solves possible maintenance problems as it is easily accessible without having to loom down the entire suction system.

The low cost is an important point to keep in mind as although the parts are printed in polymer, which greatly reduces the total cost, it is necessary to keep this low budget when it comes to engine selection.

The range of speeds at which the engine would work does not necessarily have to be wide as it is only intended to work at a continuous and medium-high speed. This way it is not mandatory that it supports higher current values as well.

By gathering these points of motor requirements and confirming that only one motor is needed which, according to discrete steps, performs its work with sufficient torque levels for the intended purpose, it is possible to conclude that a DC motor would be the most appropriate for the intended task. This decision was also influenced by some engine units available in the company, thus avoiding the purchase of new stock for the desired purpose.

The engine chosen is a brushed 'Mabuchi' brand engine with reference 'RS-540SH-6527' (RCSearch, 2020). This motor runs on direct current and its specifications are shown in Table 4.1 below.

Table 4.1. Specifications of the brushed motor selected (RCSearch, 2020)

Voltage	4.8 V ~ 0.6 V
No load	23400 rpm – 9 V – 1.6 A
Max efficiency	20040 rpm – 9.55 V – 6.8 A – 316 g/cm torque
Shaft size	3.175 mm
Shaft length	12 mm
Mounting holed	25mm x M3
Weight	160 g
Dimensions	36 x 58 mm

Based on the characteristics presented it is possible to verify that it is suitable for the task at hand, despite having higher than normal voltage and current values. Its low weight and high speed and torque values are very positive specifications for its optimal performance.

In order to visualise the system as a whole, the engine used is presented, through 3D visualisation, in the Figure 4.14.

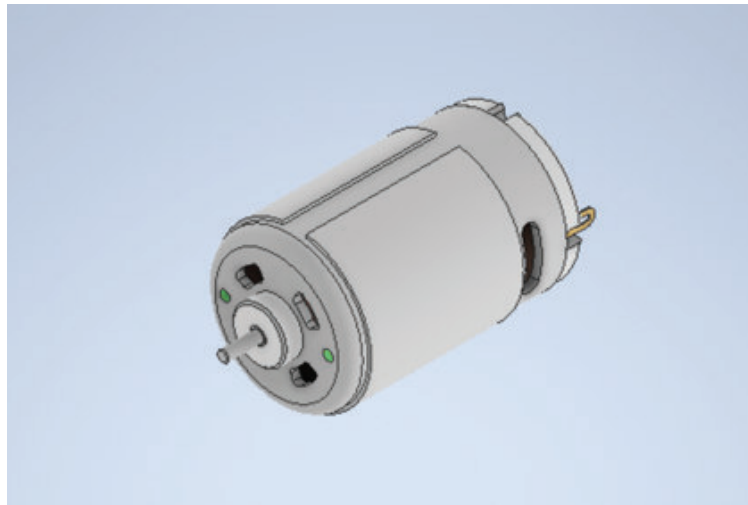


Figure 4.14. Suction system DC motor in 'Autodesk Inventor' (Martin L., 2020).

Now with the engine type and specific model chosen it is possible to analyse all its dimensions and assemble it with the motor support's CAD model for a perfect fit.

Its small size and simple geometry make it possible to conceive a direct and not very complex mooring to the turbine. However, it is necessary to place it in a position that facilitates its removal for maintenance or replacement.

In this way the DC motor is attached to the top of the Hoover with the aid of two screws, allowing the shaft to be upright and correctly positioned inside the rotation zone. This is because the motor shaft is responsible for the moment of rotation of the turbine in the developed project.

In the following Figure 4.15 is represented the actual representation of the motor that has been selected. In this model it is possible to identify, on the face opposite to the motor shaft, two metal terminals where the electrical connection is made so that the motor can be powered.



Figure 4.15. Suction system DC motor (RCSearch, 2020).

4.2.4 Structuring the Virtual Assembly

In order to check whether the dimensions assigned to the drawn components were the correct ones, it is recommended to make a virtual assembly before the production of the parts. This assembly may not be 100 % reliable because it is done through relationships between part geometries, but it is very useful to predict if a certain connection or position would work as expected. The complete assembly of the suction equipment is shown in Figure 4.16 hereafter.

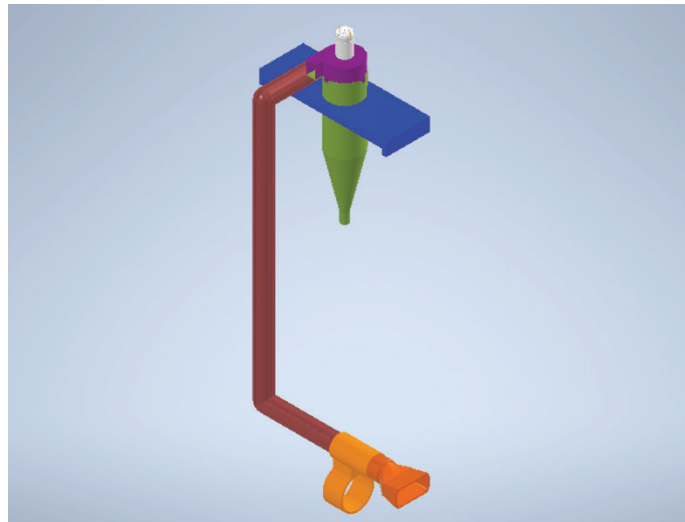


Figure 4.16. Suction system drawn parts assembly.

The structure of the entire suction system appears complete and presents no known or expected error in all connections between the parts. The holes drilled in the upper part of the engine support seem ideal for the engine fitting on that face.

The turbine is attached to the motor shaft which in itself is also coupled to the motor support part, thus making a solid and rotating connection between two parts and the engine.

The holes on the outside ring of the motor support part coincide perfectly with the holes on the top of the body, thus proving to be able to include screws with a corresponding diameter.

The suction tube is represented three-dimensionally as if it were a non-flexible part just for ease of representation. However even with this designed model it is possible to verify that both the outer and inner diameters appear to be correctly dimensioned so that the connection relationship between the tube and its auxiliary parts occurs without any error identified.

Once the entire virtual assembly of the suction system has been structured and checked, it is possible to proceed to the simulation stage based on CAD models, but without considering the pipe and auxiliary parts as the pipe is not completely identical to the actual model.

4.3 Implementation of System Elements

The implementation of the system elements is the stage of mechatronic project development that brings together knowledge from various subjects of engineering. Based on these domains it is possible to interpret the project to be developed and ensure that it is considered executable from different points of view.

In this chapter, virtual simulation technology is used to predict equipment behaviour. The simulation of natural or provoked phenomena, as a rule, is a stage prior to the production of the parts that would constitute the prototype of the mechatronic project. This occurs at this stage of the project because it aims to eliminate the waste of raw materials and obtain results without them being tested concretely. The project of the vacuum system was no exception to the suggested sequence of events.

4.3.1 Fluid Dynamics Analysis

In the world all the surrounding objects are affected by the dynamics of fluids that involves them. Calculating analytically the occurrence of all these changes caused by different fluids is something quite complex since a single solution is never presented and the equations used are complex to interpret.

In order to simplify all this process of analytical calculation the computational test of fluid dynamics, also known as CFD, was developed.

An online simulation software platform called 'Simscale' was used to perform this type of simulation applied to the suction system.

Since the air inside the vacuum cleaner does not exceed ~ 100 m/s, a simulation of the incompressible fluid flow type was selected. In order for this simulation to occur, it is necessary to create two new CAD models using a three-dimensional modelling software.

When rotating parts such as pumps and fans are used, it is always necessary to create a rotation zone. The rotating zone is an axially symmetrical volume that involves all rotating parts and at the same time should not touch any walls that do not rotate. The rotating zone corresponds to the entire volume where the turbine is revolved and is represented in Figure 4.17.

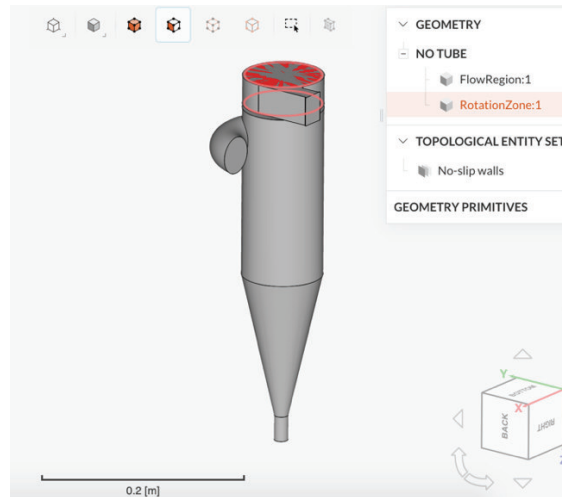


Figure 4.17. Rotation zone of the suction system.

The other preparation needed is to generate a new flow volume CAD model. This model is done by subtracting the rotor blades and the housing from the interior space of the equipment. The result of this preparation must be a mould of the internal volume of the suction system corresponding to the volume occupied by the gas, in this case air, in the equipment in simulation. The representation of the flow region is in Figure 4.18.

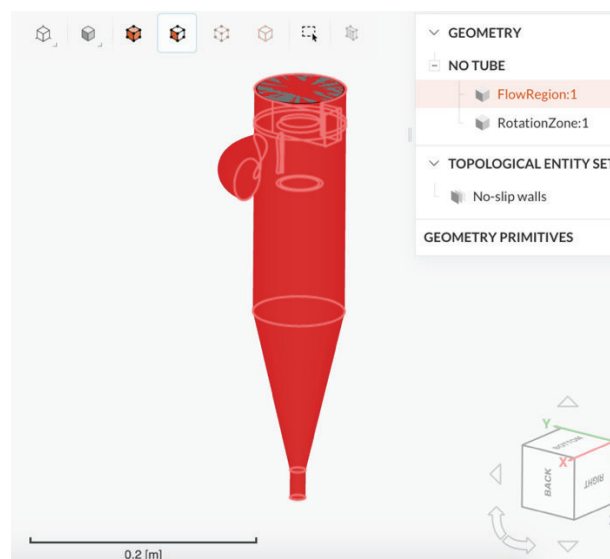


Figure 4.18. Flow region of the suction system.

After creating these necessary CAD models, it is possible to start inserting data for the simulation of incompressible flow. Initially it is required to define the material where the values entered for the air characteristics are $1.529 \text{ e-}5 \text{ m}^2/\text{s}$ of kinematic viscosity and $1.196 \text{ kg}/\text{m}^3$ of density and the flow region is selected to represent the occupied volume of air.

Then the standard values of initial conditions were not changed but boundary conditions were assigned. Since the suction air volume is on average 1 kg/s the same value has been assigned for the velocity inlet for the inlet face. For the air outlet surface, a pressure outlet value of 0 Pa was given.

In addition, border conditions of the wall type have been appointed. One of the rotating wall types where the upper face of the flow region was selected and as it is intentional that it does not move even though it coincides with the rotation zone, a rotation speed of 0 rad/s was inserted. The other condition of the wall type created was to give the exterior faces of the Hoover, excluding the entrance, exit and the upper face without rotation, the characteristic of no-slip walls.

Once all the border conditions have been met it is necessary to create the rotation zone within the advanced concepts. To create a MRF rotation zone, the pre-modelled volume of the same zone is selected, with an origin in its centre, and include the z-axis movement with 2450 rad/s of rotation speed. This value has been selected for the rotational speed since the engine has 20040 rpm at maximum efficiency. It is also necessary to introduce some final recommended values so that the simulation occurs smoothly and optimally. These values are general for fluid tests with built-in turbines (SIMSCALE, 2020).

As the last step before the run, it is necessary to redefine the mesh. The sizing option was automatic, and the small feature suppression value entered was 1e-5 m resulting in 39.1 M cells and 8.9 M nodes. This mesh resolution led to the formation of too many cells and nodes which made it impossible to complete the running test by overcasting the number of core hours of data processing. The error announced with the mesh resolution introduced in the first running test is shown in Figure 4.19.

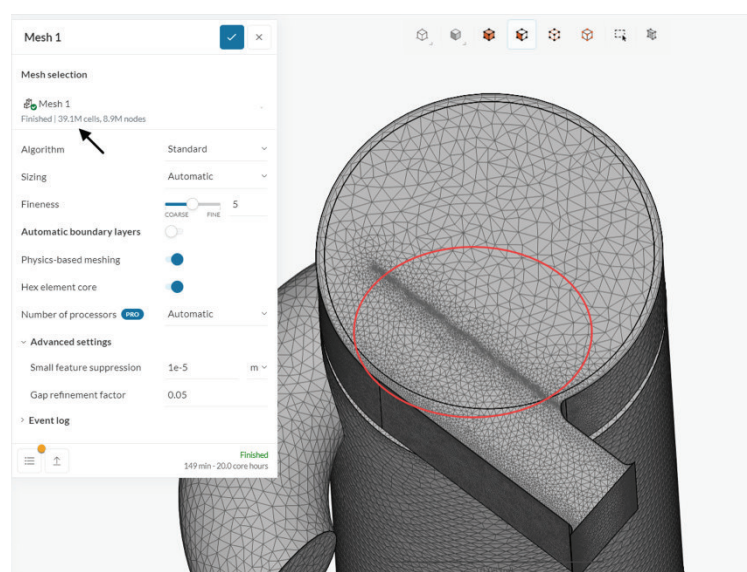


Figure 4.19. Mesh representation error with 1e-5 m of small feature suppression.

Once the value of small feature suppression is changed to $1e-4$ a smaller number of cells and mesh nodes are formed so that it is possible to run a test without any error.

The results of the flow simulation are very positive. It is possible to verify that the air circulates inside the suction system in the correct directions and expected to create suction at the air intake.

It also shows air vortex formation inside the body due to the air escaping from the central cylinder to the rotation zone, due to the impeller suction force. It is this air vortex that makes it possible to separate the air from the particles it contains.

A cut was made according to a y-plane in y in order to better observe what is happening inside and the visualisation of vectors was activated in order to check the path of air circulation according to what was mentioned. This representation of the vectors with colours according to the magnitude of air velocity is present in Figure 4.20.

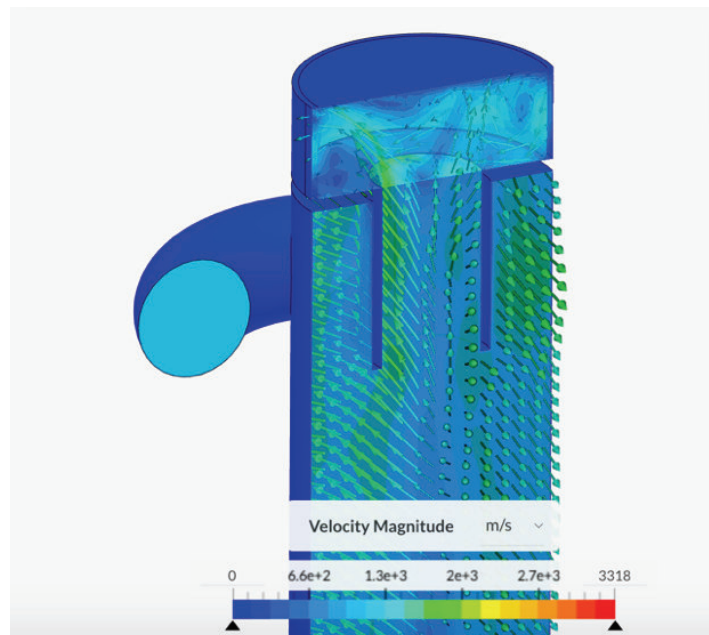


Figure 4.20. Representation with air trajectory vectors inside the suction system.

The vectors follow a cyclone path within the body volume and rise to meet the turbine. In order to better observe and analyse this vortex area, the particle trace option is activated, with visualisation according to the same cutting plane. This display option is shown next in Figure 4.21.

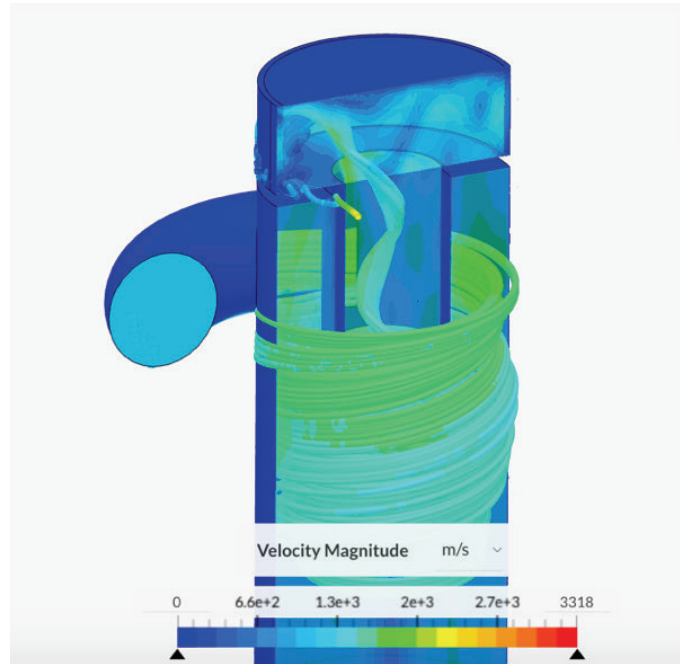


Figure 4.21. Representation with particle tracing inside the suction system.

By calling into question all the results of the air flow simulation it is possible to conclude that the geometry designed for the parts present in the presented suction system would be functional. Since the present air flow path coincides with the expected and ideal one, it must fulfil its function in the cleaning of foam particles during the operation of the CNC machine.

Therefore, it is possible to give the green light to the process that follows the simulation made with regard to airflow.

4.4 System Integration and Verification

In any mechatronic project there must be a stage of integration of the system designed in the environment for which it was designed. This integration involves confirming the synergy and correct synchronous operation of the different parts of the system with each other and with the industrial environment in which it is located. For this purpose, it is necessary to produce the parts designed and tested by virtual simulations and include an electronic circuit that provides the necessary energy to the mechatronic system.

Once the integration is completed, it is necessary to make a final assembly of all the components that are part of the suction system and check that it works as planned, thus making the verification process.

4.4.1 Production and Adjustment of the Drawn Parts

After obtaining pleasant results in the virtual simulations, the drawn parts were converted into STL files so that they can be produced using 3D PLA printing technology. This material is a thermoplastic polyester popularly used due to its low production cost through recycled materials.

The equipment used for printing the parts was the '3D FLSUN-QQ-S2'. The printer of this type has a construction volume of 255 mm x 360 mm which allows the production of large parts positioned vertically. This model is shown in Figure 4.24 below.

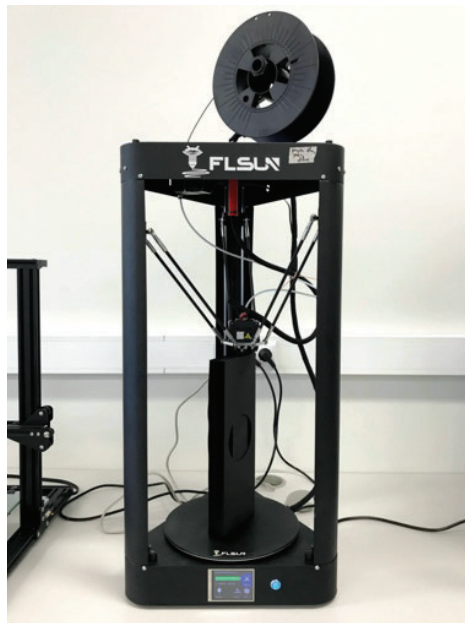
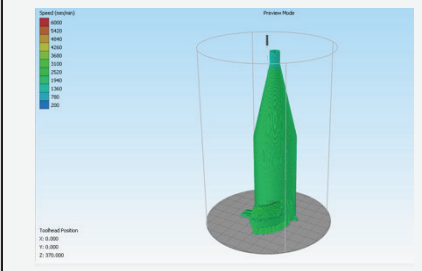

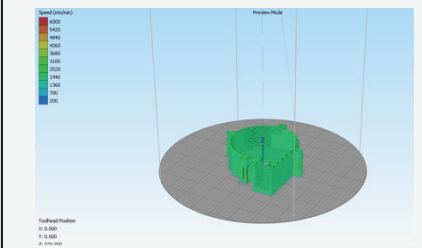

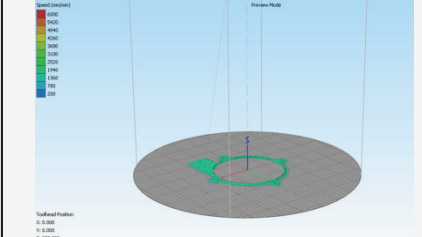

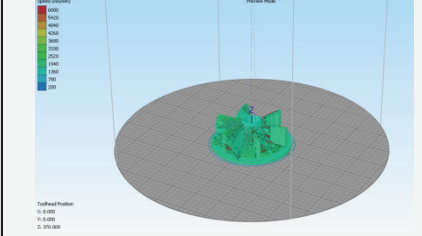

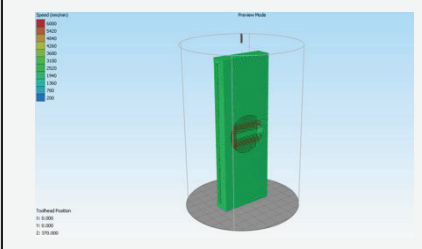

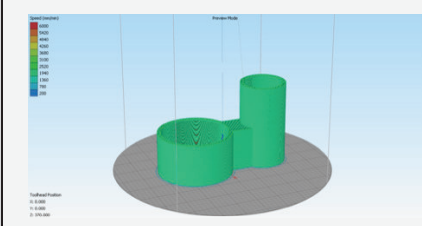

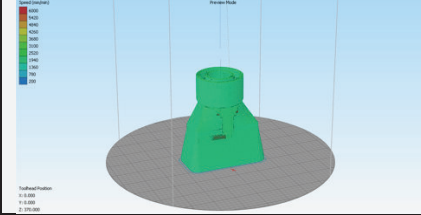



Figure 4.22. 'FLSUN' printer used for printing the parts of the suction system.

The printing times, respective representations of the position in which the pieces are printed and their final product shape, are shown in Table 4.3 that follows. The conversion of the CAD files to a '.gcode' file that is read by the 3D printer was done with the help of the 'Simplify3D' software.

Printing characteristics were input in order to optimise the process. A 15 % infill was considered for all parts except the dust plate which was printed with 20 % infill. The extruder temperature was ~ 196 °C which made its trajectory at a speed of 2800 mm/min.

Table 4.2. 'Simplify 3D' printing post-processing and printing time of the parts

Name	'Simplify3D' Inspection	Printing Time	Final Product
Body		23 h 30 min	
Motor Support		5 h 5 min	
Gasket		31 min	
Turbine		2 h 57 min	
Dust Plate		21 h 40 min	
Tube Holder		8 h 17 min	
Tube Adaptor		7 h 14 min	

After a total printing-time of sixty-nine hours and fourteen minutes, it is possible to develop all the parts necessary for a first assembly to be done.

Once completed printing the parts designed specifically for the first prototype of the suction system, it is necessary to remove the support material from them. The support material is used to facilitate the printing process, reducing printing time in some areas and also to be able to produce parts with certain complex geometries.

Once all the stock has been removed and if none of it is still trapped inside the holes, the system can be assembled for the first time in order to check the quality and robustness of the parts and how they interact with each other. This assembly test is essential in the creation of any prototype when it comes to develop a mechatronic project. This way it is possible to confirm all the tolerances that were considered in the creation of the part design and also to confirm if it would be necessary to make more replicas with some changes to achieve desired improvements. The best way to know if something works is to test it.

During the assembly process of the parts some unexpected errors occurred. The gasket designed to help in sealing and unifying the top and bottom of the Hoover was actually playing little part. As it was unnecessary to use it and as it was tested to join the motor support and the body without it and solved perfectly, it is removed from the project.

Another unforeseen event, apparently more complicated to solve, was the connection of the engine shaft to the central hole of the turbine. This fitting was designed with proper tolerancing and with consideration of the minimum printer resolution used of 0.05 mm. When the shaft is connected to the turbine it is so connected that the turbine can only be removed for maintenance or replacement reasons by destroying the turbine itself. As this procedure is not feasible, the same model of the turbine is produced only this time in UV sensitive resin in order to make the association of the parts smoother.

Manufacture was done on the 'Prusa' resin printer and for its conversion from CAD file to a '.sl1' masked file 'Prusa Sliced' was used, where it is possible to preview and edit the media creation and know the estimated time until the end of printing. The following Figure 4.25 allows the preview of the turbine manufacture which is expected to take 5 h 28 min.

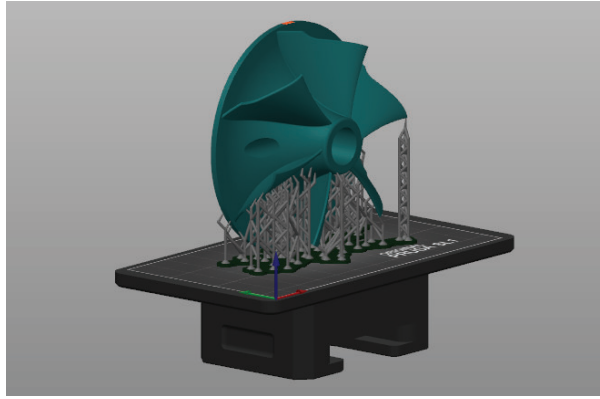


Figure 4.23. Post-processing treatment of the CAD model for resin turbine printing.

The material on which the turbine has been built is quite resistant but ends up breaking more easily in regions with less thickness, such as the turbine blades. The printer used is the 'Prusa SL1' model and is represented in Figure 4.26 below.



Figure 4.24. 'Prusa SL1' printer used for turbine printing.

Like any component made on this equipment, the turbine after the printing process had to be bathed in isopropyl alcohol to remove the excess resin that did not sinter. Then it is dried and undergoes a UV hardening treatment using a machine for this purpose, which is shown in Figure 4.27.



Figure 4.25. UV nail dryer used for the resin part hardening.

Once the hardening treatment of the made turbine has been completed it is possible to re-test its fit on the engine shaft. This occurred perfectly but although the printer used had a maximum resolution of 0.025 mm, higher than previously used, it was still not possible to remove the turbine once it was placed in the correct position by pressure.

It was not justified to repeat prints of the same model with thousandths of unit adjustments on CAD models, as only material would be wasted, and it would be more difficult to find a solution.

All other holes were tested, including those fixing the motor to the motor support, and were correctly positioned and dimensioned for the fittings that were designed. So, it wouldn't make sense to alter any other components of the suction system other than the turbine.

That said, another model was designed for the turbine fitting. The solution found to no longer need to destroy the turbine to remove it from the engine shaft once fitted was to design a part that makes the intermediate connection between the turbine and the shaft. It consists of a pin that, when fastened to the shaft, allows it to be connected to the turbine by means of a geometry fitting that does not come loose during the rotation of the turbine. The auxiliary side holes to align the engine shaft with the central axis used in the previous model were not considered in this model because they are no longer needed. The designed engine shaft pin is shown in Figure 4.28.

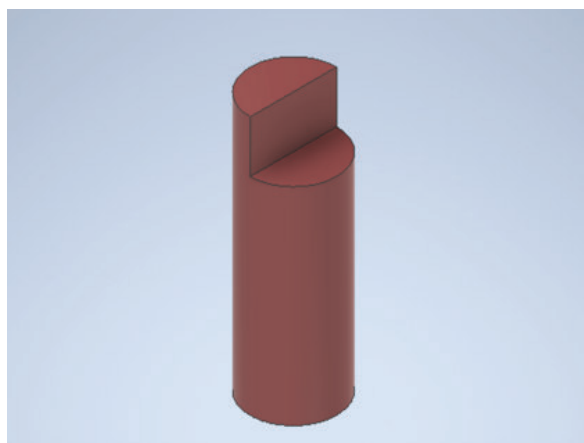


Figure 4.26. Suction system shaft pin 1.0 part.

This pin, also made in resin, is properly inserted in the bottom of the impeller. The geometry of the half-cylinder fitting at the top prevents the turbine from slipping during the operation of the Hoover. The new model of the turbine designed and fabricated to fit the pin is shown sectioned view in Figure 4.29 that follows. This model already features the central cylinder, which was open, now completely closed and with only one hole at the bottom corresponding to the reverse of pin volume.

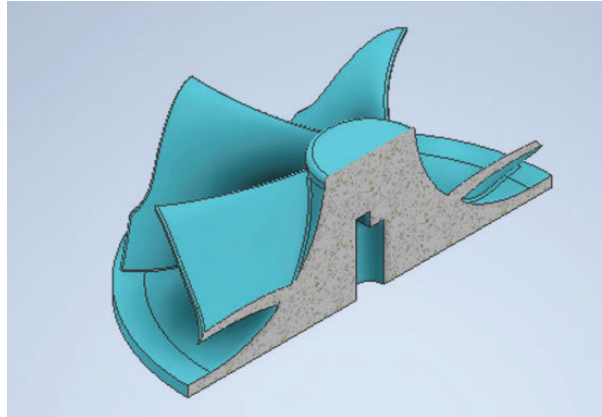


Figure 4.27. Half section-view of the suction system turbine 1.0 part.

The presented model has made significant improvements in terms of the intended linkage. However as when the assembly with the rest of the parts is carried out, the turbine falls by gravity. This happens when the impeller is facing up with the hole where the pin is inserted. Thus, due to the weight of the turbine, even during its rotation, the impeller started to detach and scrape on the upper part of the body wearing out.

A new version was then designed for the fitting pin which can be seen in Figure 4.30. The pin diameter was increased to improve adhesion and the upper fitting geometry was changed to a cross shape with the intention of centralizing the lashing force during rotor rotation.

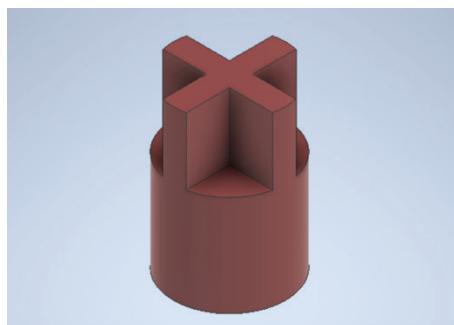


Figure 4.28. Suction system shaft pin 2.0 part.

As expected, the turbine model has also been changed according to the new pin. Unfortunately, this connection model did not show the intended result when tested. Although a new connection piece was created to solve the problem, the plug-in pin that brought the project closer to its final shape was not enough to keep the turbine fully fixed to the speed the engine delivered.

Based on this analysis of the problem and looking forward to the solution for a perfect fit of the engine shaft to the turbine a new pin is designed and produced. This new design features a more simplistic geometry. Since the fitting of all pins to the engine shaft was ideally happening, the arbitrated hole

diameter was kept and instead of presenting a fitting geometry at the other end this time presents only one other hole to be inserted a screw that also crosses the turbine guaranteed as soon as they stay together. It is possible to view the CAD model of a turbine and pin assembly according to the new model referred to in Figure 4.31, also using a section view.

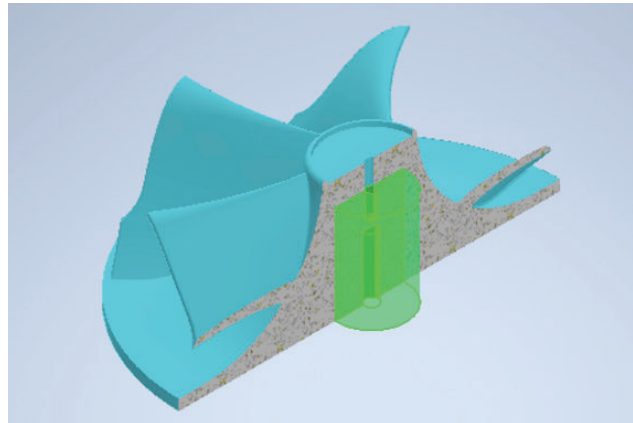


Figure 4.29. Half section-view of turbine 3.0 in assembly with shaft pin 3.0.

This architecturally designed fitting technology has worked perfectly. The following Figure 4.32 shows the complete and ideal connection between the engine, shaft pin, turbine and engine support, with the help of an M2 type threaded connection screw.



Figure 4.30. Suction system top parts assembly.

Once the biggest problem of the parts has been solved, it is necessary to continue checking and analysing how the system and its components are integrated.

The assembly of the equipment has been improved by connecting the upper part to the rest of the body and in this way inserting the vacuum into its support called dust plate. The connection of the upper and lower part of the suction system was done through four M5 screws that fit perfectly in the holes designed and printed for them.

As estimated, with this model of the suction turbine and the pin integrated in the rest of the suction system it is possible to check air suction of the circular inlet and outlet in the rectangular orifice next to the turbine. Once the assembly has been carried out, all the connection regions between the parts and the Hoover slots have been verified, ensuring that there are no gaps where gas escapes to the outside.

In order to seal the pipe connection from the tube to the rest of the equipment well, hot glue was used ensuring that no air escapes. The assembly of the suction system, with the exception of the auxiliary parts of the suction pipe, is shown in Figure 4.33.



Figure 4.31. Suction system parts assembly.

The auxiliary parts to the tube are not included in the assembly presented nor are they corrected because they have different dimensions than expected and their perfect fitting was only possible thanks to solutions that occurred at the time of integration of the equipment in the CNC.

Once the suction system is assembled, an electronic circuit capable of feeding all the equipment must be installed.

4.4.2 Electronic Circuit Connection

The starting point to find out what is needed in the Hoover's motor supply circuit is to test it. It's an imperative task to be completed on behalf of checking air leaks after the assembly of the equipment. Firstly, it is used a 6 V and 4.5 AH rechargeable battery. The electrical circuitry used in this test was trivial as only positive and negative terminals were directly connected to the respective DC motor terminals. This test was successful as the suction system worked perfectly. There was a high suction force at the entrance area of the adaptor tube and the turbine ran without any interruption causing equally high air output through the upper exit area.

Despite the positive results and the fact that it is possible to predict good simultaneous operation with the machine during the machining process of the foam block, it is necessary to note that an intrinsic aspect to the use of a battery.

As described, the battery provides 4.5 AH which means that although it provides the 4.5 A circuit in one hour, this is only an average ratio for continuous operation of normally 20 h. This means that it provides the circuit with as much amperage as it needs, and can be much higher than 4.5 A, incurring higher battery losses. The battery used in this first electrical connection test is present in Figure 4.34.



Figure 4.32. Rechargeable battery WEIYAN.

Because the battery always provided the circuit with the necessary amperage value, the circuit had to be tested with an adjustable power supply to check at which voltage and amperage values the motor operated most optimally. For this test a 'Uni-Trend' DC power supply 'UTP1305' was used which recorded values of 3.5 V and 4.88 A for good DC motor performance.

With this registration the most recommended is to use a 5 V & 25 W switched power supply in the DC motor power circuit. In order to connect the power supply to the company's electrical current an electrical plug was implemented. In the following Figure 4.35, it is possible to see that the place where the power supply of the suction system was placed is the same compartment where the manual controller of the spindle is inserted.

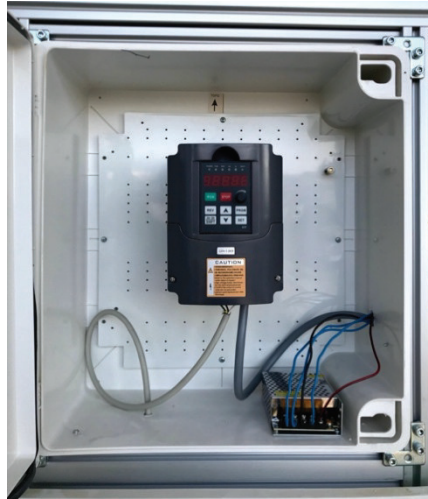


Figure 4.33. Spindle manual control box now with built-in power supply.

A switch has also been added to the mentioned circuit in order to have direct access to the circuit suspension and connection. This switch was implemented on the front acrylic wall of the CNC machine which was drilled with a drill whose diameter corresponds to the interior of the switch fixing it in a practical position for the operator. Figure 4.36 illustrates exactly where the switch was placed.

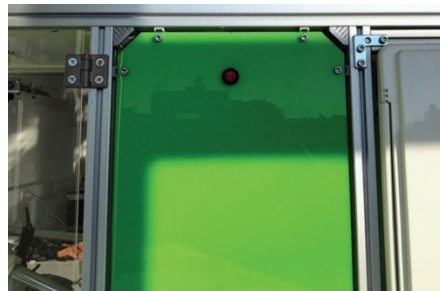


Figure 4.34. Position of the switch on the front side of the CNC machine.

In addition to the electric cables, a 5 W ceramic resistor was added to complete the electronic components used in the DC motor supply circuit of the suction system. The motor when connected directly to the source presents a peak of consumption quite large for its start. In this start-up as the industrial source has a protection block to avoid burning its components, the motor starts and after one turn stops.

This is why the role of the resistance in this circuit is to stabilize that same starting peak in which the source does shutdown. To this is added a set of shutdown fins because the lower the temperature, the better its performance would be. Its position in the circuit, as easy to shape industrial wires were used, is as immobile as possible in front of the air outlet orifice of the suction system. This way it is guaranteed that it is constantly cooled. The inclusion and position of the resistance in the system circuit is present in Figure 4.37.



Figure 4.35. Resistor used in the suction system circuit.

This inclusion of the suction system and its electrical supply circuit in the automatic machine has brought certain advantages and improvements to the machine, including the organisation of all the electrical wires inside the machine with clamps and having passed all the connections to the electrical current to a single, strategically positioned electrical extension. In order to make it easier to observe and analyse the complete electronic circuit of the suction system, it is useful to use the following Figure 4.38.

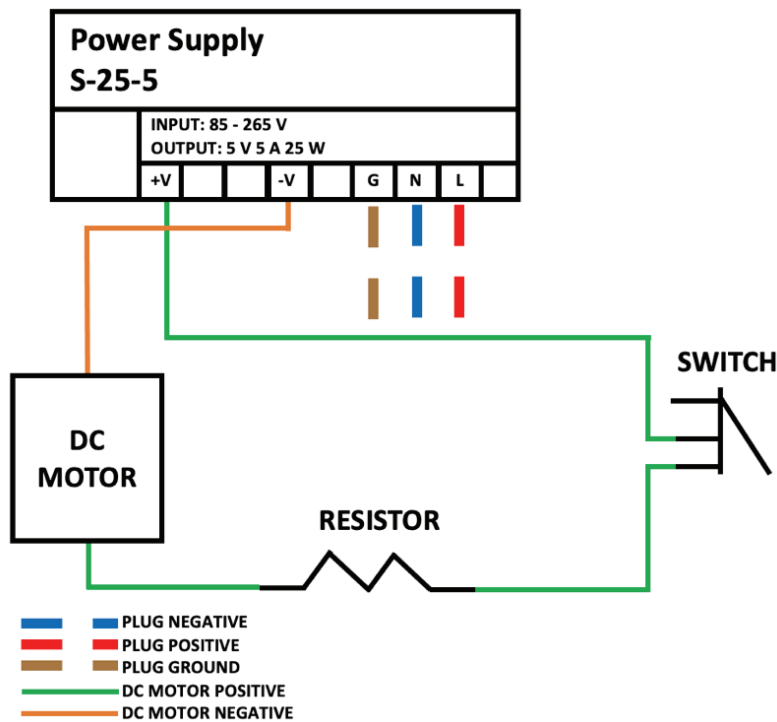


Figure 4.36. Suction system electronic circuit.

All the connections between the components of the circuit have been made with the use of electronic cables of industrial use that present less flexibility than the conventional ones so that it is possible to fix them in more strategic positions and without disturbing other objects that are close by. The cables were

welded with the help of a manual welding station, using tin as the welding material. Some protective sleeves have also been placed around some junctions.

The suction system is fully functional with this supply circuit. All electronic connections have been checked and are in final phase.

4.4.3 Suction System Integration in the CNC Machine

Since the parts produced are already well integrated in the system and in functional operation with each other it is necessary to check the full inclusion of the entire mechanism with the implementation and fixing of the hoover in the automatic machine.

The dust plate that had been perfectly dimensioned in its design is wrapped around the upper structural beams. Since it is not easy to capture an image of the interior of the CNC where the suction system was placed, as the assembly integration ran as planned in the 3D model, with the aid of the 'Autodesk Inventor', it is possible to check the position and volume occupied by the already prototyped suction system in Figure 4.39.

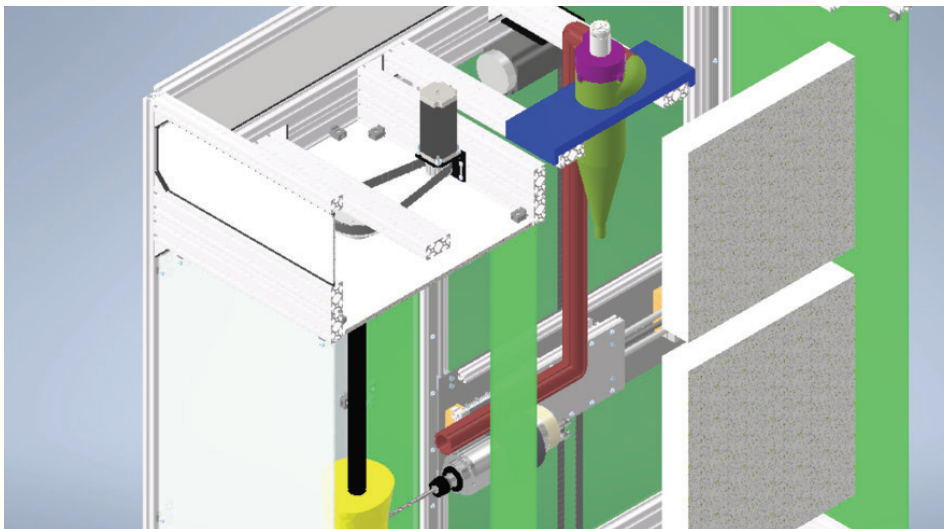


Figure 4.37. Suction system assembly implementation first analysis.

As it is possible to check the auxiliary parts to the pipe are not present as it was not possible to include them directly in the assembly of the suction equipment. In order to understand the cause, there is more space than expected between the auxiliary parts and the tube and spindle, a metrology test was performed on the parts in question. This test of annotation of different measurements using a calliper is shown in the following Table 4.4.

Table 4.3. Recording test of measurements of Tube Holder and Tube Adaptor parts

Part		Measures [mm]			Average [mm]	CAD Dimension [mm]
Tube Holder	Bottom cylinder (Minor diameter)	80.00	80.40	80.50	80.30	79.70
	Bottom cylinder (Larger diameter)	89.35	89.85	90.50	89.90	89.70
	Top cylinder (Minor diameter)	45.00	45.00	45.00	45.00	45.00
	Top cylinder (Larger diameter)	55.00	55.05	55.02	55.02	55.00
Tube Adaptor	Inside cylinder (Minor diameter)	25.60	25.55	25.55	25.57	25.00
	Inside cylinder (Larger diameter)	33.80	33.75	33.55	33.70	33.00
	Outside cylinder (Minor diameter)	44.30	44.65	44.70	44.55	45.00
	Outside cylinder (Larger diameter)	53.86	53.45	53.95	53.75	53.00

Although some CAD dimensions do not have very disparate mean measured values, there are some important dimensions in the fitting of the tube holder and tube adapter to the spindle and tube respectively that are not as pleasant.

The origin of the problem may have been some printing error but in order to reduce the unnecessary spending of raw material alternatives to reprinting the parts are presented.

As far as the tube holder is concerned it fits perfectly in the spindle with some gap and allows the tube to enter its upper orifice without any problem. A clamp has been placed to stabilize the part during the operation of the spindle so that it does not move due to the clearance with the vibration. The following Figure 4.40 illustrates what was mentioned.



Figure 4.38. Tube holder assembled to the spindle with a clamp support.

The tube adapter fitted into the tube, but the gap did not allow it to stay fixed for long which was not good as the spindle brings immense vibration to the machine and in turn to the suction equipment.

In order for it to be fixed to the tube, withstanding vibration, and always positioned for the best particulate aspiration area, two holes were made in the top and bottom extremities of the larger cylinder of the tube adaptor. In order to tighten the tube to the smaller cylinder by compressing the gap and ensuring the connection to the tube two M2 screws were placed corresponding to the diameter of the holes made.

The following Figure 4.41 represents the adaptor tube already included in the system and able to continue even during the operation of the machine.

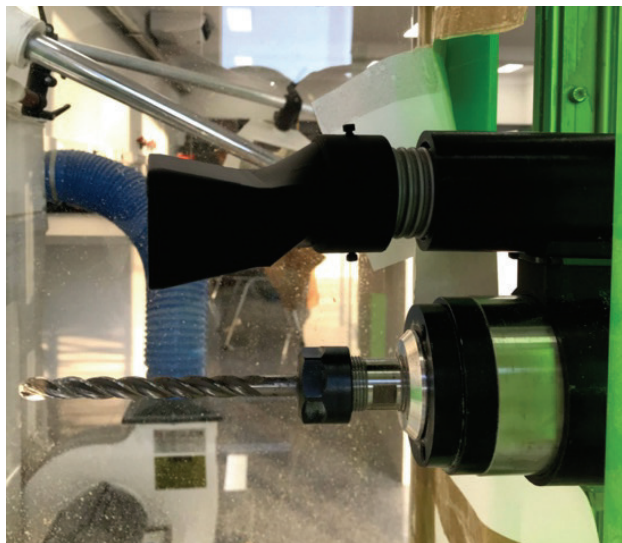


Figure 4.39. Final assembly of the tube auxiliary parts in the CNC machine.

Now all parts are well placed and connected to each other and to the machining centre, including those that contained errors in some of their dimensions. Thus, the electronic system responsible for supplying energy to the engine, the mechanical parts designed and produced specifically, and the machining centre studied and analysed in its entirety, are in perfect synergy and almost ready to work simultaneously for as long as necessary.

The final representation, totally similar to the actual result, of the system integration in the machine tool can be seen in Figure 4.42.

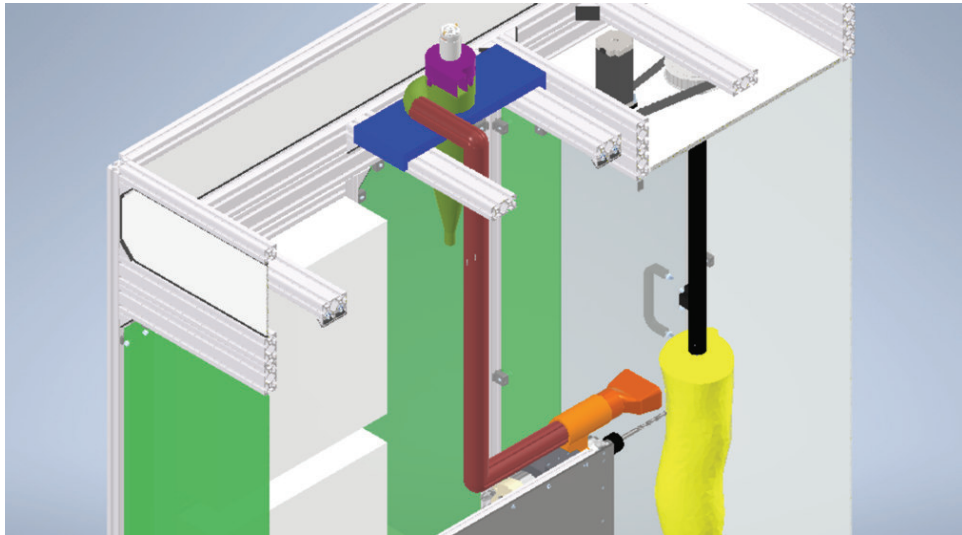


Figure 4.40. Suction system implementation with the new parts.

All the pieces together found their ideal and functional place already inside the equipment. However, before re-inserting the rear acrylic wall that has been removed to access the inside of the machine, it is necessary to include a method of draining the rubbish that comes out at the bottom end of the Hoover body to an area of the machine accessible from the outside, with all the acrylic walls correctly positioned.

A hose whose inner diameter is compatible with the outer diameter of the outlet channel has therefore been connected to this foam dust evacuation canal, providing a strong and stable connection. The bottom end of the applied hose is inserted in a fully grounded waste accumulator bin, making it easy for the operator to pour out from inside the aspirated particles during the machining process. The following Figure 4.43 represents the drainage system incorporated in the suction system, thus completing the integration and verification process.

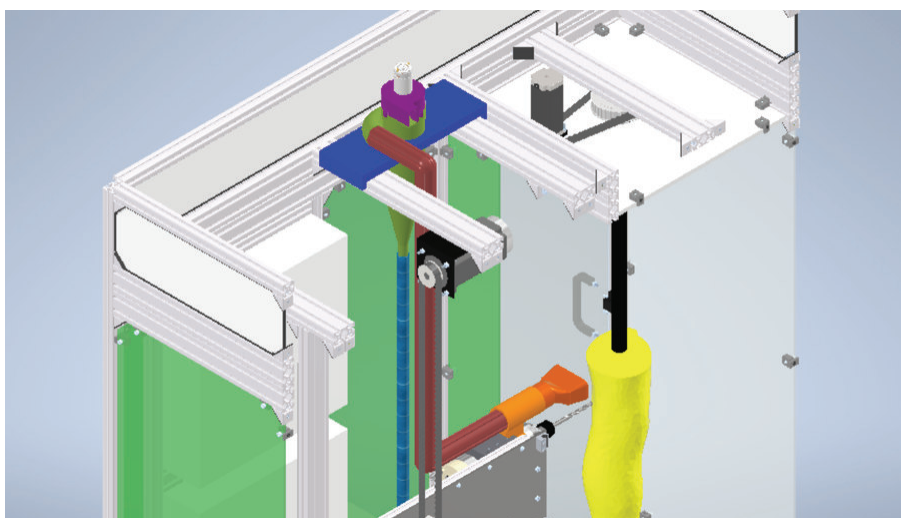


Figure 4.41. Suction system implementation with drainage system in the CNC machine.

4.5 Validation and Transition

This chapter, although being a final step in the mechatronic project methodology, contains much importance in the creation of a mechatronic project. Its validation is complementary to the entire verification process that has been carried out throughout the project and after the integration of the system.

It is in this stage that the project is classified as valid or not according to its flaws or possible missing improvements. There is a record of recognised problems that have been identified during or in the final phase of the submitted project in order to plan for their resolution in future projects.

The completion of the project should be drawn up including these points and with consistent argumentation based on the results of the simulations carried out. Once this procedure has been completed, the project can either be transferred to a possible marketplace or become the sole and only model in a company.

With regard to the design of the CNC machine improvement it fully respects the functionality requirement for which it was designed. The suction system is capable of sucking up the foam particles suspended in the air when they are pulled out of the mould block during machining. These particles are sent through the tube into the body of the Hoover without any hindrance. Once inside, the aspirated air is sent back outwards while by gravity the particles fall through the lower outlet of the suction system. Once they cross this outlet, they pass through the inside of a hose to a rubbish container placed on the floor for easy access from the bottom of the machine. Figure 4.44 below demonstrates the final appearance of the suction system, integrated into the CNC machine, fully operational.

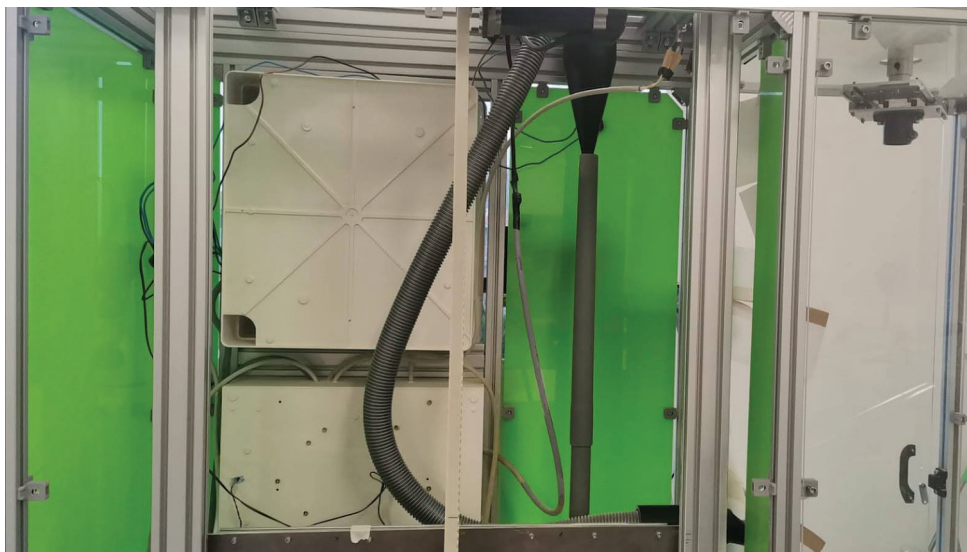


Figure 4.42. Suction system built-in to the automatic machine.

Since it is a vacuuming system it would be of great interest in the project to present analytical results such as performance, among other features on how air specifically flows inside the equipment. However, due to the lack of measuring equipment, it is not possible to measure the exact value of speed at which air enters or exits the suction system. These values could be measured directly with the use of an anemometer.

However, although these calculations would not be relevant, the suction equipment is capable of cleaning 10 g of foam dust for every minute of operation. Figure 4.45 below shows some chips that have been sucked in rather than randomly released from inside the automatic machine.



Figure 4.43. Foam particles sucked in by Suction system.

All suction and cleaning operations are given as planned and the CNC machine suction system could even be applied to other machining centres of similar functionality or geometry, though the marketing of the product is not one of the goals of the project.

However, it is always necessary to apply a critical sense with attention to detail when identifying possible improvements. In the vacuum system the designed parts would not be a main focus for improvement as they all perform their function perfectly. The electronic circuit results and provides the necessary energy for the continuous and long-term operation of the motor.

It is then possible to conclude that the conceivable improvement of the suction system would be to change the motor by another one with greater power in order to feasibly be able to suck a bigger amount of foam particles into the air. Therefore, it would only be necessary to change a small number of dimensions in the printed parts and analyse the circuit to know if it would be able to feed the new engine.

The final result of the suction system was surprisingly positive and can therefore be considered a valid and viable project.

5 CONCLUSIONS AND FUTURE WORK

This section presents the conclusions, drawn from the project, based on the results obtained and with a view to the requirements initially stipulated.

Improvements to the equipment that was developed are also presented. This brings together possible future work to be developed so that the cleaning system presents increasingly satisfactory results.

5.1 Conclusions

The project carried out and described in this dissertation, followed a certain path based on some conclusions drawn during its development.

The project itself was born from an important outcome. When the CNC machine was examined, its problem of dirt, caused by the foam particles released during its operation, gave rise to the need for a specific equipment responsible for cleaning it. This seemed to be the best solution to the detected disadvantage.

The parts designed and architected for the suction system respected the selected dimension model and presented a good synergy between them. Despite the fact that the gasket has been dispensed with and the turbine model replaced, it is possible to agree that this step has presented very promising results.

The simulation of the computational fluid dynamics also revealed quite positive feedback, thus fortifying that the constituent parts were ideal. It also confirmed that the suction technology would work as planned. Once the suction system is fully assembled and integrated it is possible to validate that the previous processes have been carried out correctly. The equipment has been included in the CNC machine and works perfectly even at the same time as the machine is active.

In short, it was a very pleasant project, and even though it required a lot of research as well as manual and virtual work, it was possible to find motivation with the positive results that were verified. However, with a critical view of the project, it is plausible to point out fewer good points of the developed equipment, to be taken into account in the future.

Gathering all the most crucial points of the project carried out, an article regarding the suction system was prepared and submitted to the scientific journal 'Periodica Polytechnica Mechanical Engineering', which can be found in Appendix III.

5.2 Future Improvements

There are very few improvements to be made to the suction system in the future, but they could significantly increase the project developed.

The aspiration of the particles takes place without any problem and is also correctly disposed of in the appropriate waste container. However, if it is desirable to increase the power of the equipment and thus increase the amount of air and particles sucked in, this would provide two solutions.

In order to directly increase the suction power without having to change too much to the design already developed, the DC motor can be exchanged for another one with a higher rotation speed. This way the turbine would also rotate more according to the speed of the shaft, moving more air with its blades.

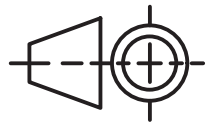
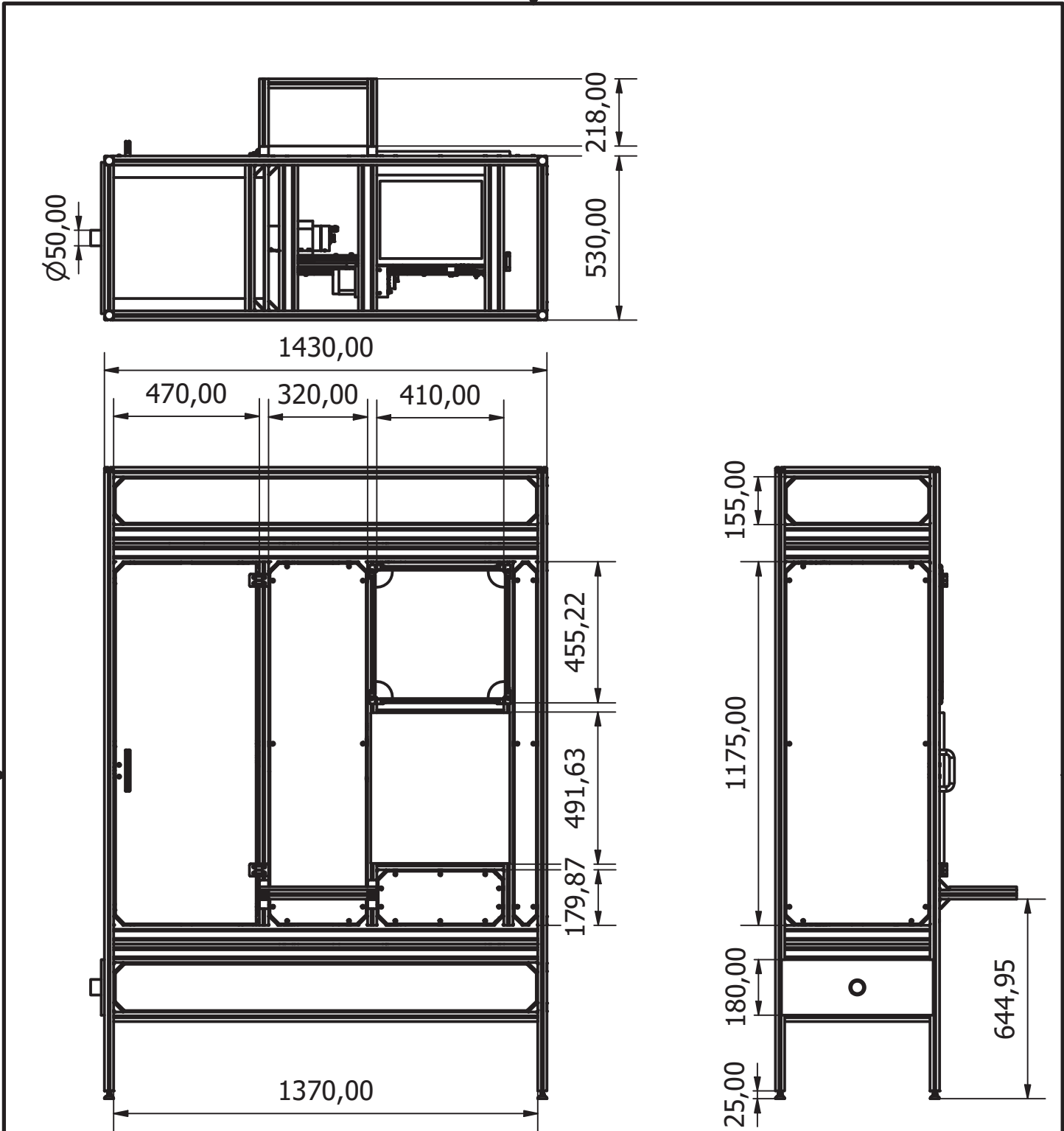
Especially if the engine replacement takes place and it is necessary to change the turbine geometry it can make a difference in the way the air is sucked inside the rotation area and expelled to the outside.

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APPENDIX I – TECHNICAL DRAW OF THE CNC MACHINE ASSEMBLY



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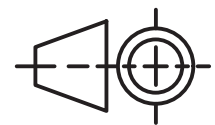
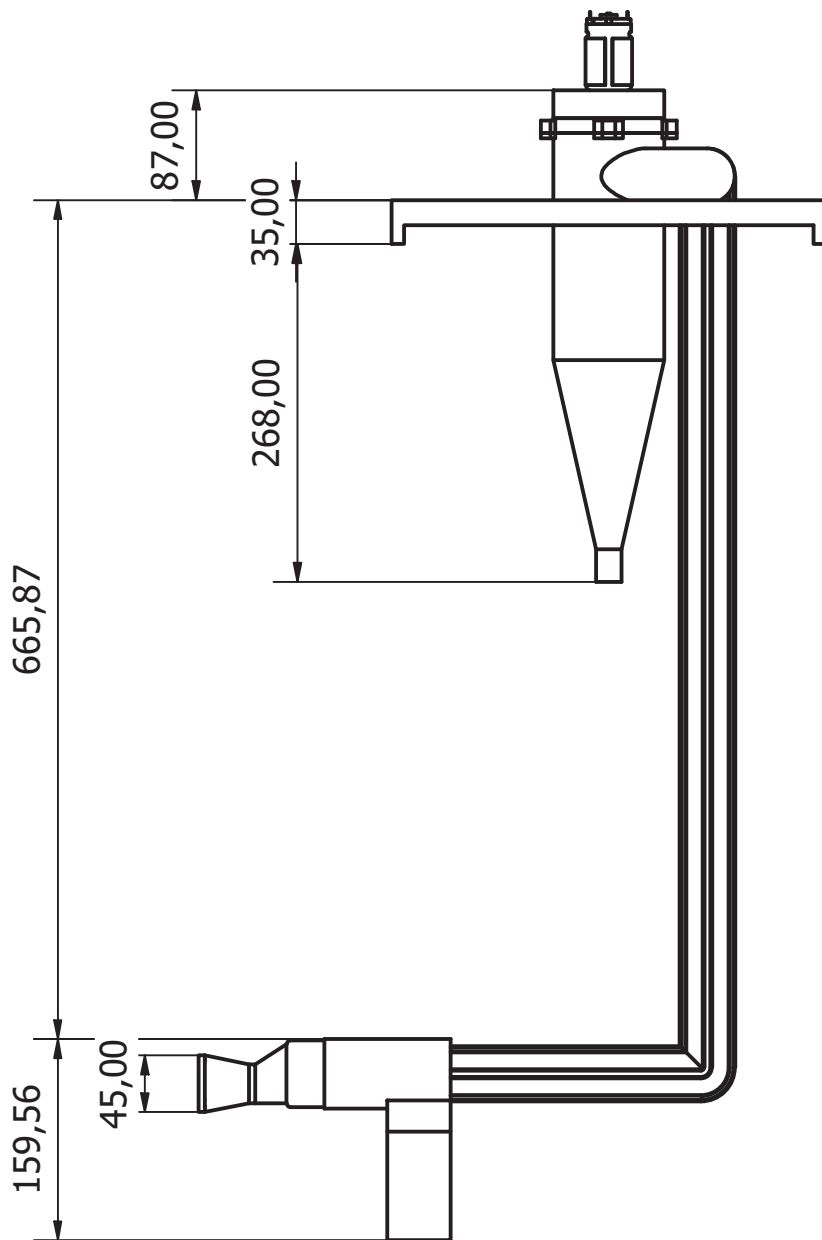
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Annexe I

Scale
1:18

CNC Machine Assembly

APPENDIX II – TECHNICAL DRAWINGS OF THE CLEANING SYSTEM AND ITS COMPONENTS



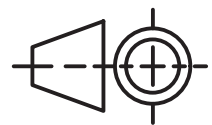
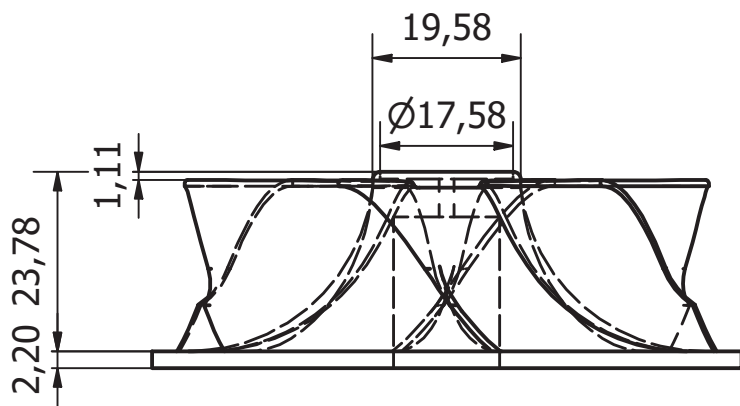
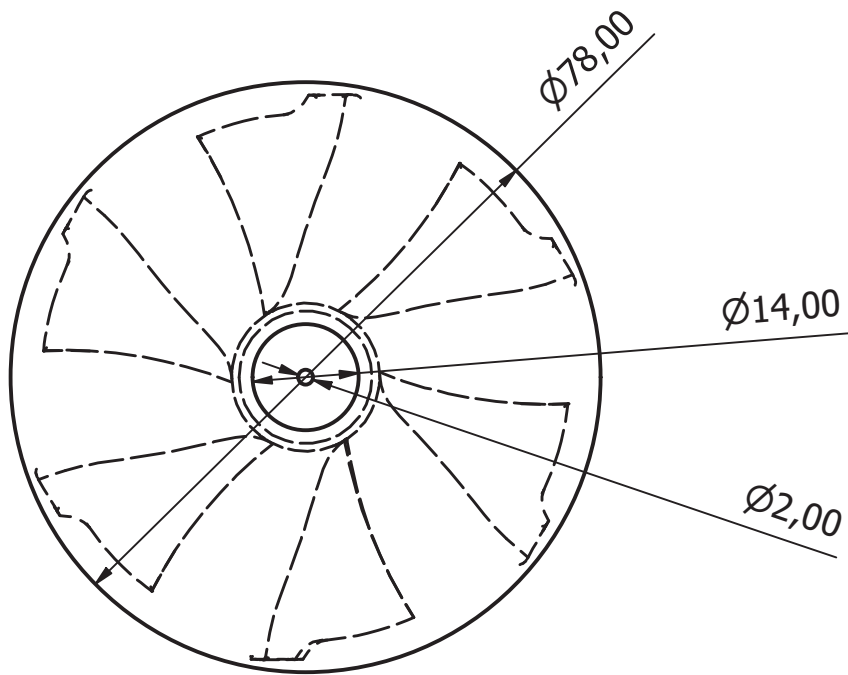
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Annexe II

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Cleaning System Assembly



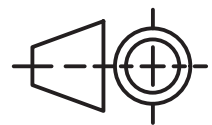
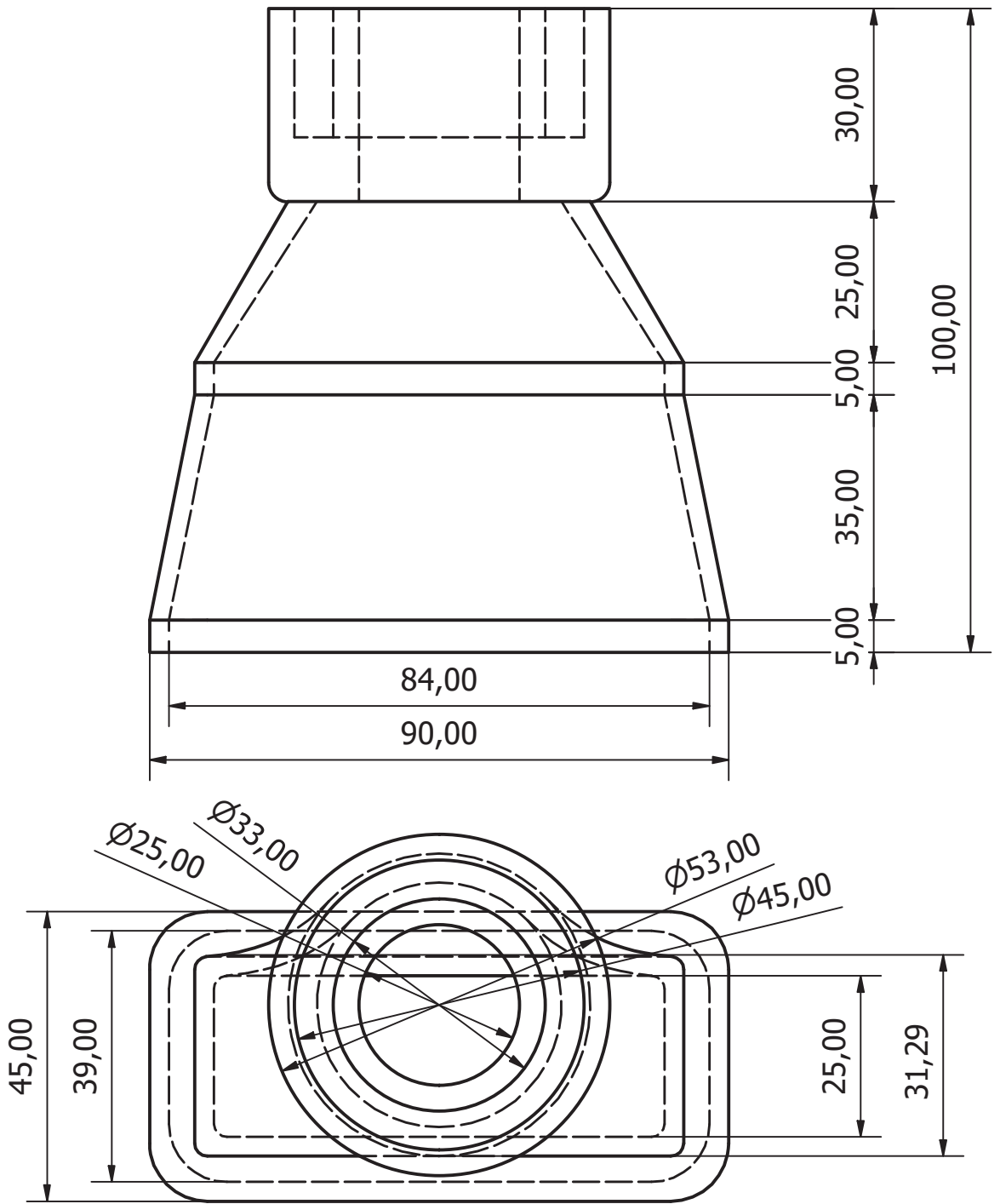
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Annexe II

Scale
1:1

Turbine Part



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Annexe II

Scale

1:1

Tube Adaptor Part

APPENDIX III – ARTICLE: ‘IMPLEMENTATION OF A CLEANING SYSTEM IN AN AUTOMATIC MACHINE’

Implementation of a Cleaning System in an Automatic Machine

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Abstract

This project consists of the architecture, design, production and implementation of a cleaning system applied in a machining center responsible for the manufacture of accessories with orthotic or prosthetic applications used in the "Padrão Ortopédico" company.

The CNC machine to be improved was also intensively investigated in order to get to know it in its entirety and to gather all possible information. The result of this process was to point out its weak points and highlight the problem of waste accumulation inside the machine which would have to be solved with a specific Hoover.

During the construction of the vacuuming system there were several parameters that had to be taken into consideration. In an initial phase of architecture and design, a model of a cyclone Hoover was selected with the suitable relationship between its dimensions. Its constituent parts were also designed and printed three-dimensionally respecting the structure chosen.

In a final phase of the project, the integration and verification took place at the site defined within the CNC, and it was verified that the system was working. The operation of the Hoover occurs without any malfunction. It takes place at the same time as the machine operations, thus resulting in a possible and positive validation and transition of the project.

Based on all the work done it is possible to criticize it positively and negatively thus pointing out possible improvements that could be made to the vacuuming system in the future.

Keywords

Prosthetic, Orthotic, CNC, Project, Vacuuming.

1 Introduction

The introduction of automatic machines capable of carrying out more complicated tasks has revolutionized the whole world of production. With the use of this technology, it is possible to apply it to various areas of activity.

In the company "Padrão Ortopédico" a CNC machine is used for the machining of molds corresponding to parts of the human body, so that from these molds prosthesis or orthotics can be produced.

Although the machining center is operational, it is possible to detect some problems that can lead to possible failures and maintenance interventions. The chips resulting from the machining of molds, made with a foam type, spread all over the inside of the automatic machine.

In order to avoid the accumulation of chips and possible damages, the presented project was developed and can be applied to similar automatic machines that have the same cleaning problem.

2 Objectives

The most urgent and important problem to solve found in the CNC machine is that the suction method found was totally impractical since its entire interior was dirty with foam particles. It is in this problem that lies the whole objective of the work carried out.

The machine used by the company was designed and assembled for all the specific functionality it performs. However, there was no information about the equipment, which has made it more complicated and time-consuming to understand the whole organism. That is why the complete study of the machine was so important in order to fulfil the purpose of including in it a suction system that would be of accessible use and easy to implement.

During the project, smaller but equally important objectives were also considered, such as spending as little raw material as possible, using recycled materials or components, thus reducing waste. In addition to reducing the costs associated with the project being a priority, the focus has also been on selecting local businesses to meet the needs as suppliers of necessary components.

3 State of art

Mechatronic products use interdisciplinary procedures during their process of conception. For a better approach during the creation its easier if it followed some topics. 'VDI 2206' is a guideline that gathers the steps to solve obstacles encountered or draw attention to important points that must be considered. These considerations are exposed in a wide way but in the end brought together in a V-shape model. The first scheme presented is a more generalized

model, which represents in a macro way, as shown in the Figure 1.

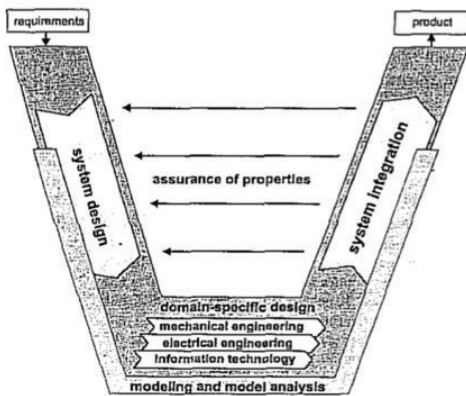


Fig. 1 V-model as a macro cycle [1].

This model only brings together a simplified logical line of work. Initially, there is an analysis of the needs that must be met by the product to be developed. After this investigation, the design of the product begins, using mechanical, electronic knowledge resources and assistance with external information found, usually through bibliography or technologies [1].

Once the model of the product is completed, it is necessary to know if it would be well integrated by its users, because although tests or simulations have been carried out, the performance during use must always be predicted [1].

In 2018 a proposal for a new improved and more specific model was presented, represented in the following Figure 2.

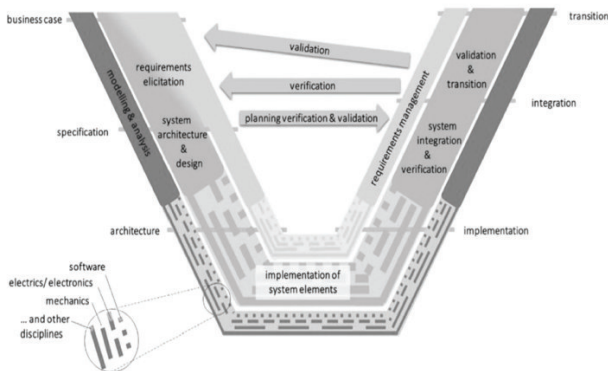


Fig. 2 New V-Model as presented at 'DESIGN 2018 Conference' [2].

This scheme is separated in three strands. Central strand stands for the main activities and tasks, inner strand designates the management and the work with necessities and the outer strand characterizes the modelling and analysis activities [2].

The main activities and tasks include elicitation of requirements, structuring and analysis, which is the basis of the project development process. A survey of the needs and desires that the target audience retains, in a formal language

and organized by lists or diagrams. This collection of data is subsequently converted to the visualization of the system in the next step [2].

In the next step all the interdisciplinary information from the branches connected to the product engineering is gathered. It is at this stage that the architecture and design of the product is defined. Uses as a basis the functional structure and the underlying action principles, bringing together the structure construction in the mechanical sense, signal flow and circuit diagrams in the electronic sense, as well as the correct choice of a software program in its modules and components, with the best interfaces [2].

After the previous phase is completed, it is necessary to implement the system elements correctly designed, dimensioned and detailed. In order to reduce waste of raw material and unexpected errors, simulations are carried out. This step is of extreme importance because it has a lot of conditions that cannot be forgotten such as tolerances to ensure the correct dimensioning of the parts, calculations and dynamic and static analyses to guarantee a good lifetime and future behavior of the product and planning of the manufacturing order [2].

Integration and verification of the system is the intermediary between the final validation and the implementation of the systems. Brings together all the conditions studied and confirmed in the different sub-systems of the product and ensure that they work correctly and synergistically [2].

In the final phase of validation and transition, a thorough check is made of all the requirements elicited for the correct use and total satisfaction of users. Whether this result is a final product, a prototype or simulation result, it is made known to the user in order to know if the whole v-model has been properly fulfilled and the project has been properly completed [2].

4 Automatic machine

For the growth of the projection on vacuum system it is necessary to know the best about the automatic machine. This includes its characteristics, as well as the identification of axes and work areas and carry out a balance between strengths and weaknesses of the machining center.

4.1 Examined automatic machine

To produce the orthotic helmets, it is needed at least 3 axes because of the geometry of the mold. It is used the revolution technique to tear the material around creating the

perfect shape of the patient's head. The parallelepiped shape of the CNC and verticality is due to the working area, also vertical, which enables the machine to further increase its versatility and produce molds for complete legs.

Hereupon the device is divided in the rotating plate named a, and the linear x and z axes, as it is possible to check on the Figure 3 below.

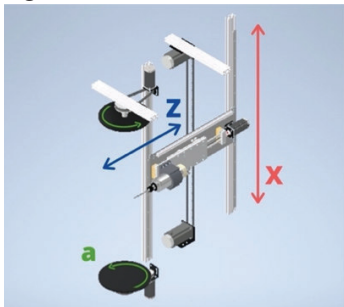


Fig. 3 Working axes of the automatic machine.

The x-axis is defined by the center of the tool table along the vertical slideways, with a total length of 1000 mm, corresponding to the maximum value.

Perpendicular to this and coincident with the center of the tool, the z axis is described. This can extend from the tip of the tool, in the receding position of the ball screw guide, to its maximum position defined by the implemented limit switch, making a total of 500 mm.

Complementing the equipment's working axes are the rotating plates that increase versatility with the angular a-axes that allow to establish positions in a range from 0° to 360°.

These axes together give the possibility to machine biometric molds in a working area with $260 \times 10^6 \text{ mm}^3$ of volume.

The automatic machine can also be divided into the transit area of the tool holder with a total volume of $480 \times 10^6 \text{ mm}^3$, the foam grain storage area and the electronic components area.

4.2 Problems acknowledged

Vacuuming the foam left by the machinery procedure was primarily done using a technique represented on Figure 4.

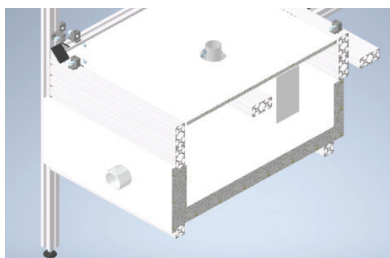


Fig. 4 Section view of the foam grain storage cavity.

On the bottom part of the working space, there is a container responsible for the collection of the foam's chip and on one of its face a hole where the conventional vacuum cleaner's tube would be inserted for the aspiration.

This method is not the most practical because of the density and weight of the chip. It's electrostatic makes it stick to the inside of the machine, in and out the working space, resulting in a more difficult way to get rid of it.

In addition to being a problem that makes the machining place not visually appealing, the motors, belts and pulleys are affected by the foam accumulated in their bowels, which can even cause the motor shafts to become jammed or stopped.

5 Cleaning system

This chapter includes the different stages of the process of projection and creation of the suction system designed as a useful and necessary cleaning solution for the machine.

Next steps follow an order similar to the topics included in the v-model of design methodology for mechatronic systems.

5.1 Requirements elicitation

The primary state of the project development process was to list the requirements that the system to be integrated would have to meet. This should give the CNC machine organs a longer life span and longer intervals between maintenance periods.

In order to solve the recognized problem for the vacuum system of the automatic machine, an investigation was carried out into the best place where the hoover should be installed.

It is really problematic that all the solid is deposited inside the deposit box, not only because of its low grain density but also because of the diameter of the particles, which makes it more likely to be lifted by the air flow and spread everywhere, polluting all the cavities of the equipment. This event forces maintenance to be done more periodically than it should be.

Originally, foam thinning occurs where the tool meets the block of material, which is considered the best place for the vacuum to occur without letting the particles escape.

As far as the unused volume inside the machine tool frame is concerned, there is only one place where is conceivable to place the suction system so as to have close access to the suction area, not disturbing the tool holder's

trajectory area. This most ideal free zone is represented in Figure 5 below.

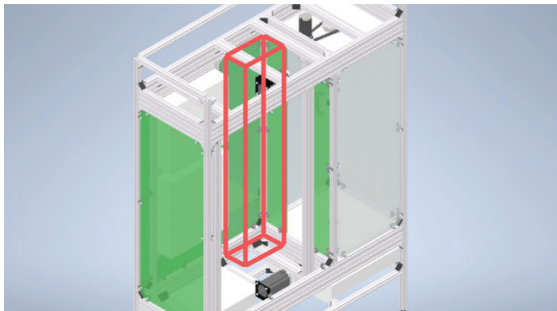


Fig. 5 Free area inside the machine.

In addition to the suction system having to suck in an area near the end of the tool and being inserted in the studied machine, in a reduced volume without interfering with the other components, another requirement has to be met. This requirement consists of allowing the user to carry out maintenance of the Hoover, change the bin and switch the device on and off without having to remove the parallel acrylic wall closest to the tool holder.

In order to ensure that no functionality requirements of the suction system are not forgotten during the development of the project, this entire list has been assembled in flowchart form represented by Figure 6.

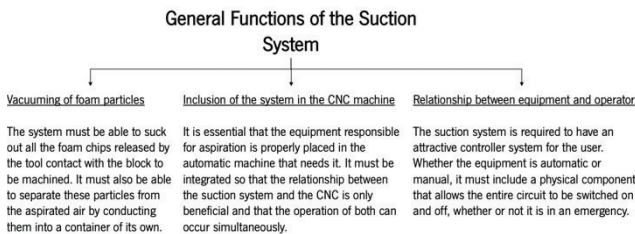


Fig. 6 General functions of the suction system diagram.

5.2 System architecture and design

Architecture and design is one of the most pivotal periods in the development of a mechatronic project. It is at this stage that the project begins to take shape.

Although it is always possible to draw inspiration from models with existing geometries, it is necessary to create a design and architecture totally specific to the intended task.

5.2.1 Suction model configuration

The suctioned material is a very small grain diameter foam and in addition to static adhesion to surfaces, it can also block cavities. Given these characteristics, the suction system must use some technology to separate this dust contained in the air without direct filtration.

A suction equipment capable of separating particles contained in the air without the use of a filter is called,

according to its function, dust collector. These can be single or multi-stage depending on the intention to separate only one or several types of dust from the vacuumed air. In this case it is only important to separate one type of dust.

There is an anatomy of centrifugal suction pumps which is the cyclone. These dust collectors are efficient in collecting and separating dust contained in the sucked gas.

Also, with similar technology to conventional hoovers, cyclone collectors have an inlet through which all the air is pulled into a depressurized area that when the turbine ends its operation, or even during it by gravity, all the waste that was in the air falls. This now clean air is sucked in by the same turbine in action, which is an impeller. It is then sent out through an outlet to the outside environment. The mentioned system is represented illustratively in Figure 7 below.

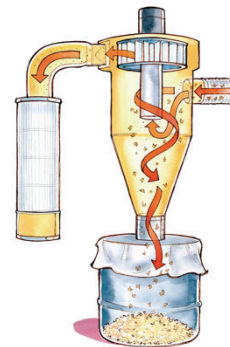


Fig. 7 Gas transit within a suction model with a cyclone system [3].

After intensive research on the strengths and weaknesses of this type of dust collector, one of the most discouraging information found was that it is not advisable to build a dust-collection cyclone because the construction and connection is somewhat complex due to its metal parts.

However, this point is easily refuted because due to current technologies and also available in “Padrão Ortopédico”, it is possible to print its constituent parts on a type of polymer, called PLA, through 3D printers.

5.2.2 Development of mechanical parts

Once it's recognized the recommended relationship between the dimensions of the cyclone type Hoover together with the necessary changes to the specific function it would perform, it is possible to design the constituent parts. All the design of the vacuuming system was carried out with the support of ‘Autodesk Inventor’ software, thus allowing the creation and preparation of parts and their assembly in CAD.

The design began with the body where air circulation and separation by gravity of the foam particles occurs. As this part of the system contains almost the entire flow region, it

should be completely sealed and should not leak anywhere. Its cylindrical and conical shape, with appropriate dimensions, helps in the air circulation process. The part mentioned is shown in Figure 8.



Fig. 8 Suction system body part.

As the inlet and outlet geometries of the suction system have been changed, it is necessary to confirm that all arbitrary dimensions respect the studied dimensioning ratios. This has been complied with measures close to diameter, height and air intake area in the body.

A new component has been designed with a geometry suitable for coupling to the body of the suction system. This part attends to support the engine to be introduced, and inside it contains the rotation zone where the impeller turbine would be inserted, thus creating different pressure and suction points at the entrance of the body, represented in Figure 9.



Fig. 9 Suction system motor support part.

This upper casing of the suction system also has an air outlet necessary for the gas to escape without particulates included. The outlet on the side of the new part's cylinder, despite being rectangular to follow the trajectory of air leaving the turbine, has dimensions whose area is similar to the standard area given by the gas outlet diameter.

External holes were also drilled to coincide with them on the edge of the upper body so that they fit perfectly and no gas escapes.

For the design of the turbine, some important requirements emerged in the arbitrage of its dimensions and geometry. The turbine must have a geometry so that the entire volume of the piece can drag as much air through its blades as possible.

The design of the turbine blades is the most important part as it would influence the performance of the air circulation within the suction system. Based on the different

types of impellers and the use of each for different situations required, it is possible to choose an ideal model for the case under study. The number of blades selected is six equally spaced blades, with a certain curvature and side cut. The design of this geometry took into consideration the aerodynamic behavior performed by the turbine so that aspiration is possible in its entirety.

With regard to the turbine mooring to the engine it was considered that it should facilitate the maintenance process of the designed device and also be possible to replace the turbine by other models to test its efficiency.

In this way the final appearance of the turbine includes an auxiliary pin, thus ensuring that the connection between the motor shaft and the turbine is safe and easy to interrupt if desirable. A screw is inserted in the face of the pin opposite to where the motor shaft will be placed, making the connection even more solid during the moment of rotation. It is represented in the Figure 10.

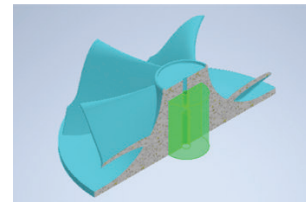


Fig. 10 Half section-view of turbine in assembly with shaft pin.

Although the parts that have been drawn may appear to be sufficient components for the construction of the cleaning system of the CNC machine, they are not. The method of attaching them to the machining center remains to be defined and planned.

As previously shown the volume available inside the machine tool, a plate has been designed with the function of mobilizing the Hoover in this volume. Although this support plate has a somewhat simplified geometry, it contains specific dimensions which have been studied and compared to the actual measurements of the CNC machine. Its length must coincide with the distance between the beams at the top of the automatic equipment and the hole inside it with a diameter with a suitable tolerance for the perfect fitting of the suction device body in order to keep it immobile and well supported without applying great tension. The following Figure 11 illustrates the mentioned drawing in three dimensions.

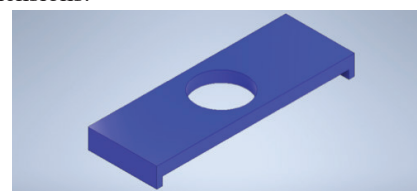


Fig. 11 Suction system plate part.

In the same way as every light fixture needs a bulb, a Hoover is also not complete without a tube. The suction tube to be included was removed from a conventional Hoover. The dimensions of this one are totally pleasant for the fitting of its extremity with the entrance hole of the cleaning system of the CNC machine.

The tube with a length of 1.50 m is suitable for the minimum size it would need if the suction equipment is to be affixed to the top of the free area of the automatic machine to the tip of the tool at its lowest level. The outer diameter of the tube is perfectly suited for an optimum fit to the inner diameter of the air intake, with suitable tolerance values range.

The architecture of the suction pipe has to be more complex. Auxiliary parts had to be designed to ensure that it is always attached to the spindle and that it vacuums according to an area suitable for the indicated suction area. These parts have been designed with tolerances appropriate to the outer and inner diameters of the pipe for the connection or support of the tubing. The part responsible for joining the pipe to the spindle of the machine is shown in Figure 12.



Fig. 12 Suction system tube holder part.

Once the part that holds the pipe has been designed, it is necessary to complement it with another piece that gives it a wider opening area. The geometry of this part must also contribute to the air intake in the suction system being always parallel to the tool and in front plane with the suction area, for a more

efficient suction. The part designed for this function is shown in Figure 13.

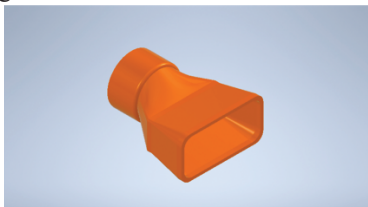


Fig. 13 Suction system tube adaptor part.

With the addition of this new auxiliary part, the suction area is now $84 \times 39 \text{ mm} = 3276 \text{ mm}^2$. All the parts now totally designed and architected it is possible to proceed to the next essential step in the projection and elaboration of a mechatronic project.

5.3 Implementation of system elements

The implementation of the system elements is the stage of mechatronic project development that brings together knowledge from various subjects of engineering. Based on these domains it is possible to interpret the project to be developed and ensure that it is considered executable from different points of view.

In the world all the surrounding objects are affected by the dynamics of fluids that involves them. Calculating analytically the occurrence of all these changes caused by different fluids is something quite complex since a single solution is never presented and the equations used are complex to interpret.

In order to simplify all this process of analytical calculation the computational test of fluid dynamics, also known as CFD, was developed.

An online simulation software platform called ‘Simscale’ was used to perform this type of simulation applied to the suction system.

The results of the flow simulation are very positive. It is possible to verify that the air circulates inside the suction system in the correct directions and expected to create suction at the air intake.

It also shows air vortex formation inside the body due to the air escaping from the central cylinder to the rotation zone, due to the impeller suction force. It is this air vortex that makes it possible to separate the air from the particles it contains.

A cut was made according to a y-plane in y in order to better observe what is happening inside and the visualization of vectors was activated in order to check the path of air circulation according to what was mentioned. This representation of the vectors with colors according to the magnitude of air velocity is present in Figure 14.

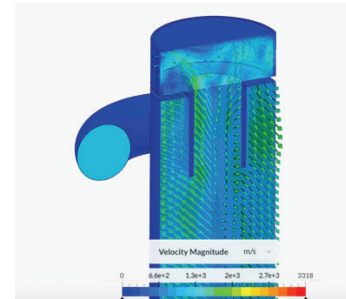


Fig. 14 Representation with air trajectory vectors inside the suction system.

The vectors follow a cyclone path within the body volume and rise to meet the turbine. In order to better observe and analyze this vortex area, the particle trace option is activated, with visualization according to the same

cutting plane. This display option is shown next in Figure 15.

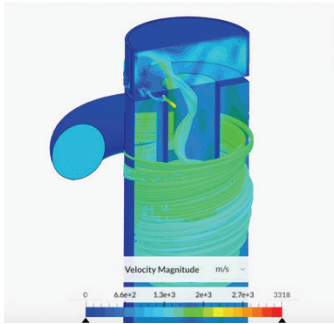


Fig. 15 Representation with particle tracing inside the suction system.

By calling into question all the results of the air flow simulation it is possible to conclude that the geometry

designed for the parts present in the presented suction system would be functional. Since the present air flow path coincides with the expected and ideal one, it must fulfil its function in the cleaning of foam particles during the operation of the CNC machine.

Therefore, it is possible to give the green light to the process that follows the simulation made with regard to airflow.

5.4 System integration and verification

In any mechatronic project there must be a stage of integration of the system designed in the environment for which it was designed. This integration involves confirming the synergy and correct synchronous operation of the different parts of the system with each other and with the industrial environment in which it is located. For this purpose, it is necessary to produce the parts designed and tested by virtual simulations.

Once the integration is completed, it is necessary to make a final assembly of all the components that are part of the suction system and check that it works as planned, thus making the verification process.

After a total printing-time of sixty-nine hours and fourteen minutes, it is possible to develop all the parts necessary for a first assembly to be done.

The system can be assembled for the first time in order to check the quality and robustness of the parts and how they interact with each other. This assembly test is essential in the creation of any prototype when it comes to develop a mechatronic project.

All the pieces together found their ideal and functional place already inside the equipment. However, before re-inserting the rear acrylic wall that has been removed to access the inside of the machine, it is necessary to include a

method of draining the rubbish that comes out at the bottom end of the Hoover body to an area of the machine accessible from the outside, with all the acrylic walls correctly positioned.

A hose whose inner diameter is compatible with the outer diameter of the outlet channel has therefore been connected to this foam dust evacuation canal, providing a strong and stable connection. The bottom end of the applied hose is inserted in a fully grounded waste accumulator bin, making it easy for the operator to pour out from inside the aspirated particles during the machining process. The following Figure 16 represents the drainage system incorporated in the suction system, thus completing the integration and verification process.

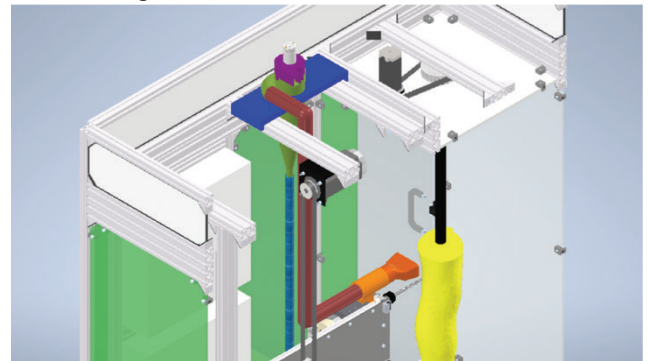


Fig. 16 Suction system implementation with drainage system in the CNC machine.

5.5 Validation and transition

This chapter, although being a final step in the mechatronic project methodology, contains much importance in the creation of a mechatronic project. Its validation is complementary to the entire verification process that has been carried out throughout the project and after the integration of the system.

It is in this stage that the project is classified as valid or not according to its flaws or possible missing improvements. There is a record of recognized problems that have been identified during or in the final phase of the submitted project in order to plan for their resolution in future projects.

The completion of the project should be drawn up including these points and with consistent argumentation based on the results of the simulations carried out. Once this procedure has been completed, the project can either be transferred to a possible marketplace or become the sole and only model in a company.

With regard to the design of the CNC machine improvement it fully respects the functionality requirement

for which it was designed. The suction system is capable of sucking up the foam particles suspended in the air when they are pulled out of the mold block during machining. These particles are sent through the tube into the body of the hoover without any hindrance. Once inside, the aspirated air is sent back outwards while by gravity the particles fall through the lower outlet of the suction system. Once they cross this outlet, they pass through the inside of a hose to a rubbish container placed on the floor for easy access from the bottom of the machine.

All suction and cleaning operations are given as planned and the CNC machine suction system could even be applied to other machining centers of similar functionality or geometry, though the marketing of the product is not one of the goals of the project.

The final result of the suction system was surprisingly positive and can therefore be considered a valid and viable project.

6 Conclusions

The project carried out and described in this article, followed a certain path based on some conclusions drawn during its development.

The project itself was born from an important outcome. When the CNC machine was examined, its problem of dirt, caused by the foam particles released during its operation, gave rise to the need for a specific equipment responsible for cleaning it. This seemed to be the best solution to the detected disadvantage.

The parts designed and architected for the suction system respected the selected dimension model and presented a good synergy between them. The simulation of the computational fluid dynamics also revealed quite positive feedback, thus fortifying that the constituent parts were ideal. It also confirmed that the suction technology would work as planned.

Once the suction system is fully assembled and integrated it is possible to validate that the previous processes have been carried out correctly. The equipment has been included in the CNC machine and works perfectly even at the same time as the machine is active.

In short, it was a very pleasant project, and even though it required a lot of research as well as manual and virtual work, it was possible to find motivation with the positive results that were verified.

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