Universidade de Aveiro Departamento de Engenharia Mecânica
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Miguel António Batista Esteves Martins

Projecto e construção de uma máquina para estampagem incremental

Project and construction of a Single Point Incremental Forming Machine

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Projecto e construção de uma máquina para estampagem incremental.

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob a orientação científica do Prof. Doutor Ricardo José Alves de Sousa, Professor Auxiliar Convidado do Departamento de Engenharia Mecânica da Universidade de Aveiro, e co-orientação do Professor Doutor Jorge Augusto Fernandes Ferreira, Professor Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro.

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palavras-chave

Estampagem incremental por ponto único, design em engenharia mecânica, projecto e desenvolvimento.

Resumo

A estampagem incremental é um processo recente que está em desenvolvimento. A sua aplicabilidade é variada pois permite a obtenção de peças funcionais em chapa metálica sem grandes custos associados. Devido a esta característica, áreas como a biomecânica, prototipagem rápida e produtos de características personalizáveis fazem deste processo um alvo de interesse.

Infelizmente, os meios de obtenção de peças usando estampagem incremental por ponto único são limitados. Normalmente faz-se uso de centros de maquinagem CNC adaptados, que devido às suas características próprias de corte por arranque de apara, tornam a aplicação da estampagem incremental limitada e ineficiente. Além disso, a oferta de mercado em maquinaria com características dedicadas ao uso de estampagem incremental requerem elevados investimentos, tornando-se assim uma solução pouco atractiva.

Um dos principais obstáculos à aplicação desta técnica centra-se no tempo de conformação elevado, principalmente quando comparado com técnicas de estampagem convencionais. Outra desvantagem deste processo é a baixa precisão dimensional, que todavia com o avanço dos estudos numéricos e com o desenvolvimento de algoritmos de correcção tende a ser minimizado.

Neste trabalho pretende-se concluir o projecto de uma máquina para realização de estampagem incremental por ponto único que teve início em anos anteriores. Este projecto tem por objectivo a obtenção de uma máquina que ultrapasse as limitações das máquinas actuais, mas não desconsiderando o factor económico. Além disso este projecto visa ampliar os horizontes para futuras pesquisas e desenvolvimento do processo, tanto na melhoria da máquina, mas também no desenvolvimento e na compreensão do mecanismo de deformação existente e aumento associado da formabilidade material.

keywords

Single point incremental forming, design in mechanical engineering, project and development.

abstract

Single Point Incremental Forming is a recent technology that is currently under development. Its applicability is diverse because it allows the attainment of functional parts in sheet metal without great costs. Due to this characteristic, areas such as biomechanics, rapid prototyping and products of customizable features make this process a target of interest.

Unfortunately, the means of obtaining parts using single point incremental forming are limited. Usually, CNC machining centers are utilized but due to their cutting-type characteristics, the implementation of the Single Point Incremental Forming is limited and inefficient. Also, the market supply of dedicated machinery requires high investments, thus becoming an unattractive solution.

A major obstacle to the application of this technique focuses on the superior time of forming especially when compared to conventional forming techniques. Another disadvantage of this process is the low dimensional accuracy, however, with the development of numerical studies and correction algorithms this problem tends to be minimized.

This work aims to complete the project of a single point incremental forming machine that began in previous years. This project has the objective of overcoming the limitations of the current incremental forming machines, but not ignoring the economic factor. Also, this project aims to enlarge the horizons for future research and development of the process, not only improving the machine but also developing and understanding the forming mechanism and the consequent effects of improved material formability.

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Chapter 1

1.1. Introduction

For centuries, man has been producing sheet metal components using different tools and techniques. A method universally applied is the use of dies and punches, manufactured in accordance with the shape and dimensions of the component. However, despite being widespread, it contains technological hindrances, such as large energy costs and very high investment, which make this process very expensive. Because of the high cost of punches and dies, this method is only suitable for mass production, where the cost can be shared with a large number of products.

On the other hand, the recent diversification in customer demand has resulted in the downsizing of the production lots. Because of this reduction the cost of manufacturing the tools needed to be reduced. This necessity gave origin to the intensification in the development of new production methods for a small lot. One of those methods is to create an incremental deformation in the sheet metal using a simple tool. The idea of incremental forming with a single tool, in the three Cartesian axes, was patented in 1967 by Leszak [1]. This method has later become very attractive, due to the advance of manufacturing technology in the fields of Numerical Control and Automation. With the massification of computer or numerical control of manufacturing systems, incremental forming can now be fully automated and tends to be more available to general public. One of the great advantages of this method is the ability to use small/simple tools that create a deformation along a defined path. The tool can be a simple hammer, a laser beam, or a water jet. One of the techniques that is receiving great attention by the scientific community and from the industry is the Single Point Incremental Forming (SPIF).

1.2. Single Point Incremental Forming

1.2.1 Description

Single Point Incremental Forming is an innovative process that has the capability of producing non-axisymmetric parts. It uses simple tools, usually a cylindrical metal tool with a flat or spherical tip. It also does not require the use of dies with the shape of the piece being produced. This eliminates the use of presses, because the forces involved in the process tend to be much smaller. Figure 1 shows the components involved.

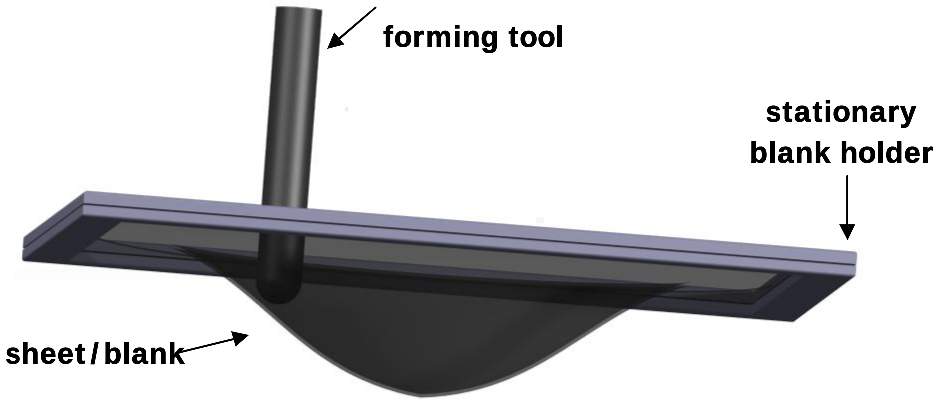


Figure 1 - Single Point Incremental Forming main components.

The deformation is performed by applying pressure on the surface of the sheet, forcing it to deform gradually. The metal sheet is usually restrained by the blankholder to avoid displacement and the flow of material into the forming area. Therefore, the whole forming operation is undertaken through the blank's thinning. The thickness of the blank at the end of the process may be related to the angle of the wall through the Sine Law (1).

$$T_f = T_i \sin\alpha \qquad (1)$$

where,

T_f – sheet's final thickness

T_i – sheet's initial thickness

α – wall angle

The forming tool is controlled by CNC software and the path is predefined by a toolpath processor. This results in an enhancement in the precision when compared with processes that have direct human intervention. Figure 2 illustrates an exemplificative path taken by the forming tool.

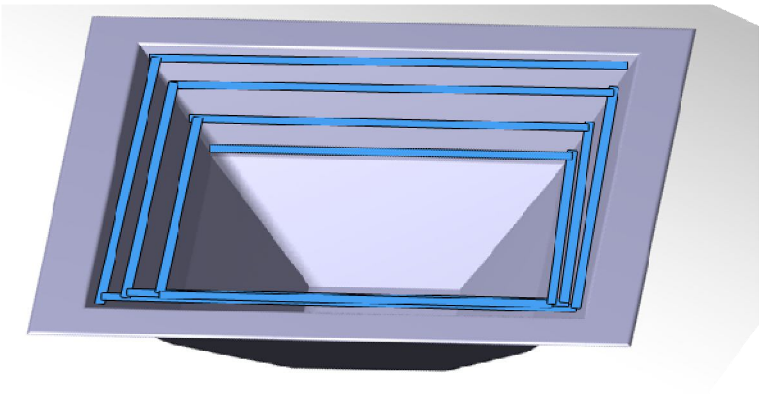


Figure 2 - Path followed by the forming tool.

Jeswiet et al. [2] resumed the advantages and disadvantages of SPIF as follows:

Advantages:

- Useable parts can be formed directly from CAD data with a minimum of specialized tooling. These can be either Rapid Prototypes or small volume production runs.
- The process does not require either positive or negative dies, hence it is dieless. However, it does need a backing plate to create a clear change of angle at the sheet surface.
- Changes in part design sizes can be easily and quickly accommodated, giving a high degree of flexibility.
- Making metal usable Rapid Prototypes is normally difficult, but easy with this process.
- The deformation mechanism based on bending-stretch and the incremental nature of the process contributes to increased formability, making it easier to deform low formability sheets.
- A conventional CNC milling machine or lathe can be used for this process.
- The size of the part is limited only by the size of the machine. Forces do not increase because the contact zone and incremental step size remain small.
- The surface finish of the part can be improved.
- The operation is quiet and relatively noise free.

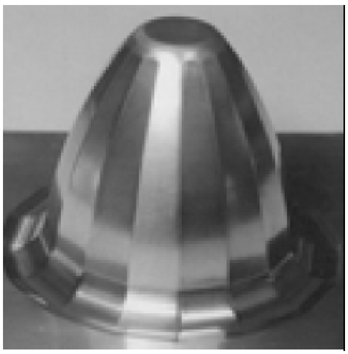
Disadvantages:

- The major disadvantage is the forming time that is much longer than competitive processes such as deep drawing.
- As a result the process is limited to small size batch production.
- The forming of right angles cannot be done in one step, but requires a multi-step process.
- Springback occurs during the whole production phase, nowadays correction algorithms are being developed to deal with this problem [3].

1.2.2 Applications

Single Point Incremental Forming has a vast field of applications, such as aerospace, automobile, home appliances industry, marine industry and even fields such as medicine and food processing [4]. It is a technology that is very versatile and can handle different kinds of materials, such as steel, aluminum, composite and polymeric materials. Table 1 shows examples of the versatility in geometries that can be achieved using SPIF.

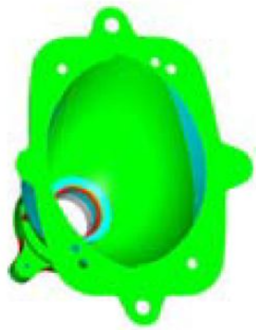
Table 1 - Different geometries achieved by SPIF [2].

		
Five lobe shape	Faceted cone	Truncated pyramid

One of the major application areas of SPIF is in Rapid Prototyping because it has the capability of attaining functional parts. Given that, the car industry had its attention focused on this process because the field of application in areas like prototypes and replacement parts were vast and profitable.

The parts shown in Table 2 are Rapid Prototypes for automotive industry. The two first parts are reflective surface of prototype headlights. The third is a heat/noise shield, which is used over exhaust manifolds [2].

Table 2 - Rapid prototypes for automotive industries [2].

IGES file		
		
2002 vehicle headlight	2002 vehicle headlight	Automotive heat/noise shield

Another area where SPIF can have a great impact is in the medical industry, particularly in the manufacture of prostheses and braces. Using Reverse Engineering (RE) it is possible to reproduce high accurate models that mimic parts of a human body or support them.

For example, a cranial implant can be easily produced using SPIF [5], [6]. The only necessary input is the CAD model, which can be obtained by lifting the form of the patient's skull. Then, this geometry is replicated in a metallic shell. An example can be seen in Figure 3.

Figure 3 - Cranial implant obtained by incremental forming [6].

Ambrogio et al. [7] and Jeswiet et al. [2] also addressed this field of application. Single Point Incremental Forming was used to produce a part that is used as an ankle support. The process began by using a non contact inspection, laser scanning, to obtain the morphological and dimensional information of the necessary body part in the form of a cloud of points. From this information, surfaces were made and ultimately a CAD model was built. Finally, via a CAD/CAM application, an ISO file was created and sent to a numerical control machine that carried out the Incremental Forming operation. Figure 4 demonstrates the different stages to manufacture the ankle support.

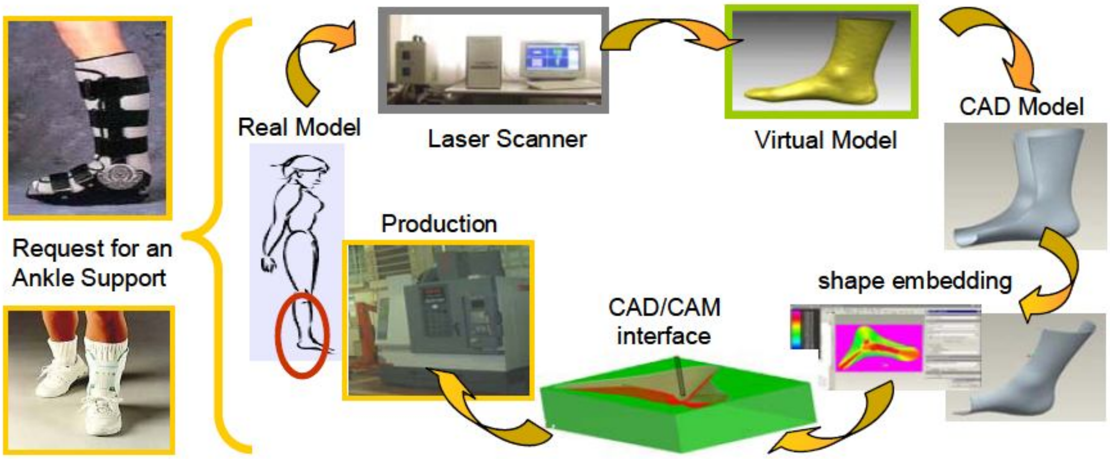


Figure 4 - The process of manufacturing an ankle support [2].

According to Maratubo [8] this type of product is ideal for the SPIF process due to its high degree of customization, and because the price of the product does not represent a major vector of competitiveness, a characteristic that is common throughout the industry for the manufacture of components for medical use.

With the development of this process areas like biomechanics can receive a great enhancement. Nowadays biomechanics lack tools to produce or transform with precision the necessary materials in to usable products. With the development of the process and new SPIF machines this obstacle can be overcame.

1.3. SPIF Parameters

1.3.1 Forming forces

One of the major characteristics that define a deformation process is the forming forces involved in it. According to Allwood et al. [9], for SPIF process the forces involved in the process can be predicted using an approximate calculation by a theoretical model. Allwood et al. [9] divided their analyses in two tool loading situations represented in Figure 5, (a) the tool travels normally to a flat sheet, causing a hemispherical indentation of the sheet; (b) during deformation, the tool moves horizontally 'around' the existing deformed area of sheet, creating a one-sided groove.

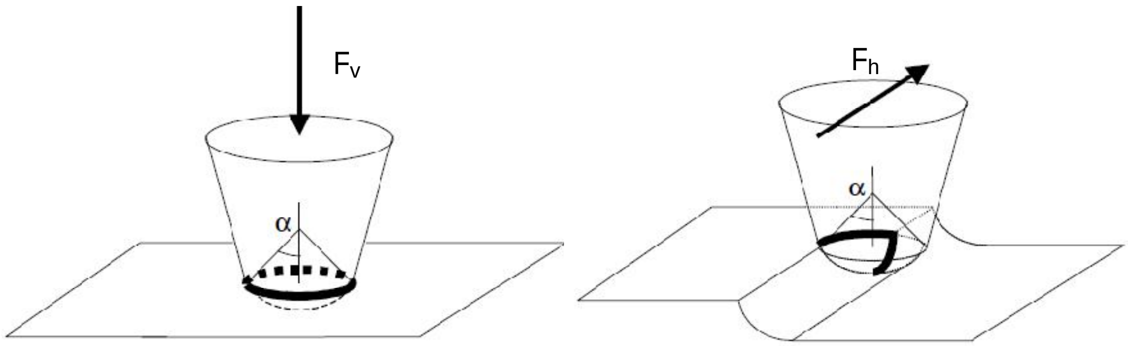


Figure 5 - Two tool load cases [9].

From the analyses of the previous diagrams the vertical force, F_v and horizontal force, F_h can be estimated by the following equations:

$$F_v = \pi \cdot r \cdot t \cdot \sigma_y \cdot \sin\alpha \qquad (2)$$

$$F_h = r \cdot t \cdot \sigma_y \cdot (\sin\alpha + 1 - \cos\alpha) \qquad (3)$$

where,

r – tool radius;

t – initial blank thickness;

σ_y – yield strength;

α – cone interior angle.

With this theoretical model, a rough assessment of the forces can be made with some swiftness. For a 1.6 mm thick mild steel, with a yield stress of σ_y = 350 Nmm^2 and considering a tool radii of 15 mm with $\alpha = \frac{\pi}{6}$, the predicted vertical and horizontal tool forces from equations 2 and 3 were F_v = 13.2 kN and F_h = 5.3 kN.

Various other authors developed experimental and numerical simulations in order to estimate the forces involved in the process [6], [9-14]. However, the parameters between each analysis are significantly different. Aspects like different materials, blank thickness, tool diameter, step size and others were combined as the authors saw fit. The following table shows some of the forces predicted/measured by different authors.

Table 3 - Measured forces by different authors.

Author	Maximum force [kN]	Method
Allwood et al. [9]	13 (vertical), 6.5 (horizontal)	Theoretical model
Duflou et al. [6]	1.46	Experimental
Rauch et al. [10]	0.9	Experimental
Jackson et al. [11]	3	Experimental
Durante et al. [12]	2	Experimental
Bouffioux et al. [13]	1.3	Simulation
Decultot et al. [14]	12	Experimental
	14	Simulation

1.3.2 Friction at the tool/sheet interface

One of the characteristics that is important in SPIF process is the interaction between the tool and the blank. This interaction can occur in different ways:

- The tool slides over the blank without rotation, but with a significant amount of friction.
- The tool rolls over the blank with its own rotation and with some friction.
- The tool rolls over the blank with free rotation and with low friction.

The control of the spindle speed allows the control of the friction between the tool and the blank during formation. Friction levels should be maintained low because friction generates heat causing surface degradation to occur. According to Kim et al. [15], the appearance of friction at the tool/sheet interface would result in the improvement of formability and delay of fracture occurrence. However, Kim et al. [15] also concluded that if the friction increased too much, the sheet would fracture.

1.3.3 Lubrication

As stated above, the existence of friction is beneficial to the formability. However, it also causes the sheet's surface degradation, therefore, in order to preserve the surface, lubricants are used. As concluded by Kim et al. [15], the absence of lubricants results in scratches on the sheet. Since products obtained by SPIF process are normally functional or in its finished form, the state of the surface is of important manner, for that reason the use of lubricants are common. Another inconvenience due to the absence of lubricants is the increase of bending loads on the tool, which could result in misalignment or even fracture.

1.3.4 Tools size and geometry

The tools normally used for SPIF have a spherical or a flat tip. This assures a continuous point contact between the sheet and forming tool. "Depending on the geometry and the material of the piece, the choice of the best tool can vary. In most instances, the ball-head tools are made out of tool steel, which is suitable for most applications. To reduce the friction, and to increase tool lifetime, the tool can be coated with or even made out cemented carbide." [2]. An example of the different geometry and tool size can be seen in Figure 6.

A wide range of tool diameters can be used, from small diameters such as 6 mm, up to a large tool with 100 mm in diameter. These are normally used for the manufacturing of large parts such as car's hoods, and require much more power because of the large contact angle involved.

Figure 6 - Coated tools (left), spherical tip tools (center), flat tip tools (right), [2].

1.3.5 Incremental step size

Surface roughness is a major concern in a final product. Therefore, the quality of the product must be granted from the beginning of the process. In SPIF the major factor in determining surface roughness is the incremental step size, Δz. The surface roughness tends to increase, as the distance between the indentations caused by the displacement of the tool on the blank becomes greater. A representation of that occurrence is shown in Figure 7.

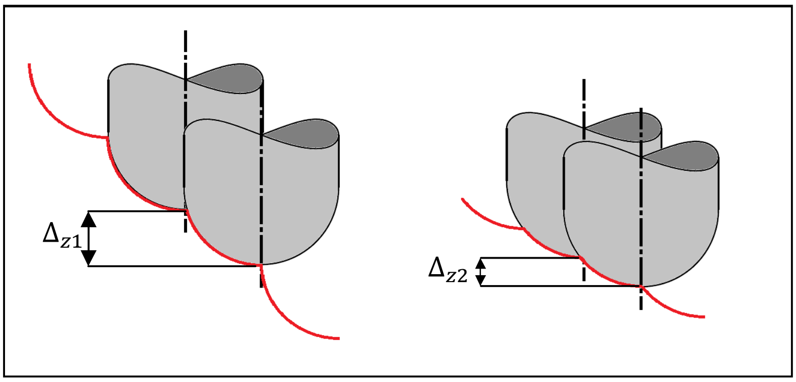
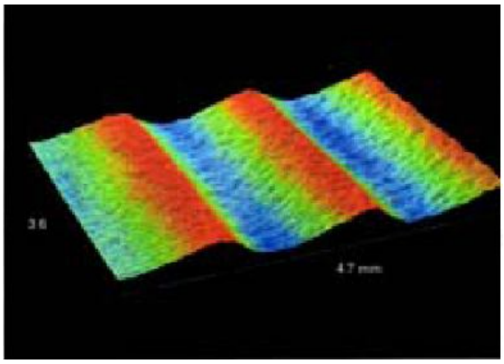
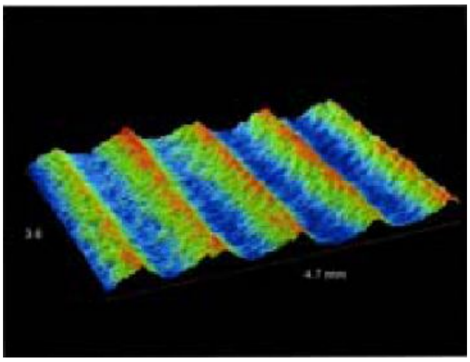
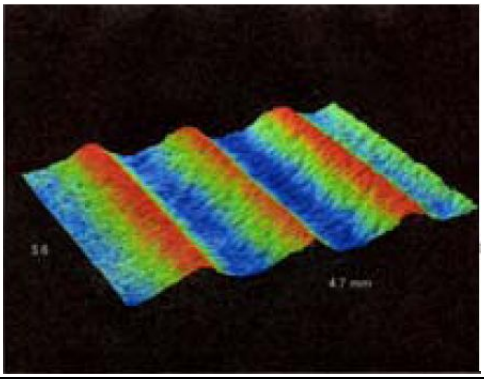
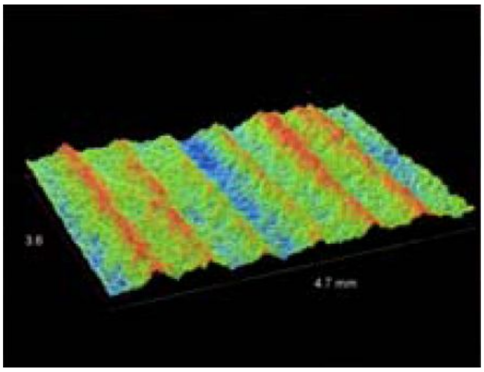


Figure 7 - Difference in surface roughness according to increase/decrease in step size.

An experiment conducted by Jeswiet et al. [2] shows different surface roughness for different pitch sizes. The profiles presented in Table 4 were obtained by white light interferometry and are 3.6 mm x 4.6 mm. The tool diameter is 12.5 mm. This is a SPIF characteristic that needs to receive some attention, since the market is very demanding in terms of quality, and because quality is related to the vertical increment, it becomes imperative to use a small increment. Unfortunately a reduction in the step size can represent a significant increase in production time. Therefore, a balance must be sought between quality and production time.

Table 4 - 3D Surface roughness for four pitch sizes, Δz [2].

	
Δz = 1.27 mm	Δz = 0.76 mm
	
Δz = 1.02 mm	Δz = 0.51 mm

1.3.6 Materials

Just as the technology to process materials evolves, so do the materials. With the rise of aerospace and biomedical applications, new materials have been created and others have seen their characteristics improved. In order to develop SPIF process, a number of materials have been tested. The more common used material is aluminum mainly because the machines where the tests are conducted have limitation in the maximum applicable force. Steel is target material for this process but do to the limitation mentioned above, only very thin sheets can the deformed. The table below resumes some of the experiments made and the results/difficulties seen while testing different materials.

Table 5 - Tested materials and their characteristics.

Author	Material	Application	Characteristics
Ham et al. [16]	AA – 5754 AA – 6451 AA- 5182	–	Thickness: 0,8 – 1,5 mm
Jeswiet et al [2]	AA – 3003 O	–	Thickness: 0,93 – 2,1 mm
Micari et al. [17]	AA 1050 O	–	Thickness: 1,2 mm
Tanaka et al. [18]	pure titanium	denture plate	Main difficulties in the production of this part were the surface quality, needing to find optimal combination between feed rate and lubrication
Hussain et al. [19]	pure titanium	–	Proper tool, good lubricant and lubrication method were required
Jackson et al. [11]	sandwich panels	aircraft interiors, car body panels, architecture panels saving weight, absorbing sound, vibrations and impact, and isolating thermically	–
Franzen et al. [20]	PVC (Polyvinyl Chloride)	complex polymer sheet components with very high depths	–
Le et al. [21]	polypropylene (PP)	different geometries	–
Ji et al. [22]	Magnesium AZ31	structural applications	Warm temperatures

1.3.7 Toolpath

There are a few ways to characterize the formation of toolpaths. One way to define it is by the direction of movement. Two common designations for the direction of movement are the direct forming and inverse forming [23].

- Direct forming – the punch progressively deforms the blank from the top going towards the maximum depth.

- Inverse forming – the punch is firstly moved down to the maximum drawing depth, and then follows a trajectory in upwards direction until it completes the process.

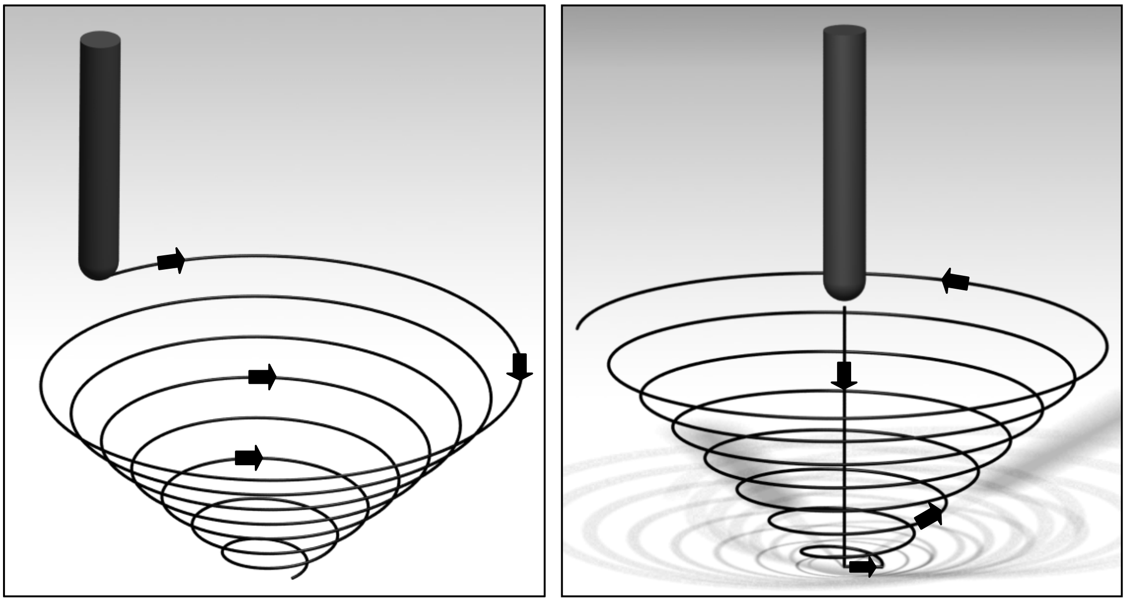


Figure 8 – Direct forming (left); Inverse forming (right).

The toolpath formation can also be defined by the type of movement. The two most used methods are contour milling and spiraling.

- Contour milling toolpath is normally defined was a finishing pass, typically characterized by fixed Δz increments between consecutive discrete contours. The disadvantage is the appearance of transition marks between layers, which also creates force peaks [2].

- A spiraling toolpath is continuous with incremental descent of the tool distributed over the complete contour of the part. The advantage is that no marks occur at step down [2].

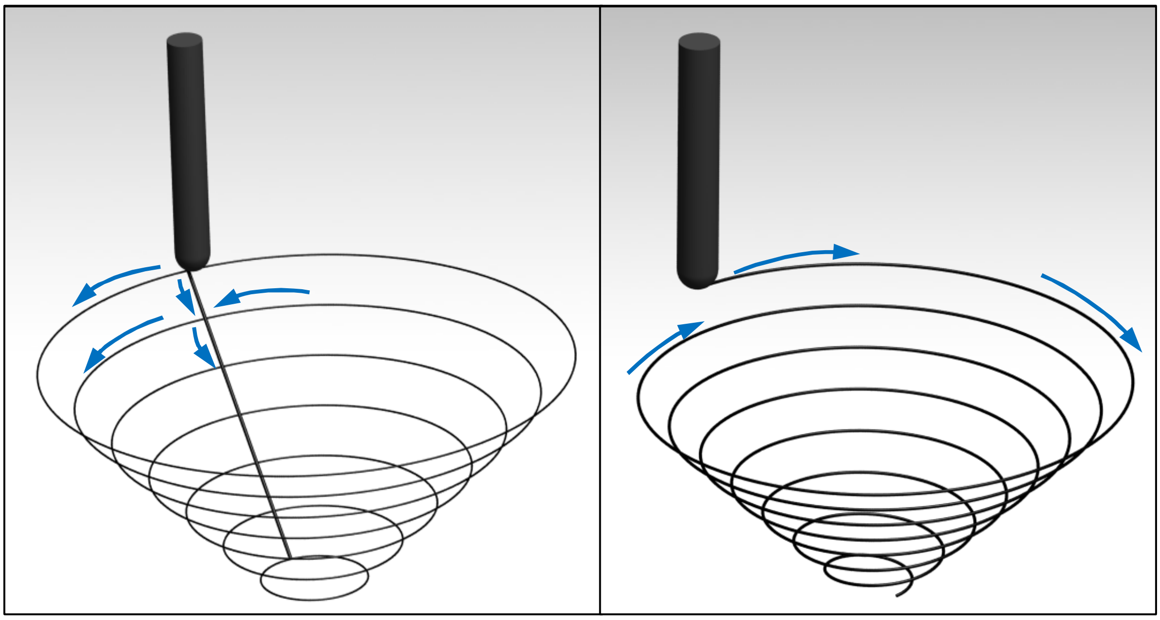


Figure 9 - Contour milling toolpath (left); Spiraling toolpath (right).

There are also multiple toolpath strategies. These include creating consecutive intermediate forms with a final passage that results in the final form or the combination of contour milling and spiral toolpath.

1.3.8 Formability

One very interesting feature of SPIF is the increase in the material formability. Although the scientific community agrees that there is an increase of formability, compared with other processes like stamping or deep drawing, it is still not clear how the mode of deformation influences the formability of the process.

Some authors state that the deformation occurs by stretching, combined with bending, which promotes increased formability [24], [25]. Other explanations are based on the presence of through thickness shear strain which leaded to the developments of extended Marciniak-Kuszinski models [26], [27]. Many experiments have been carried out and many more will be performed until a consensus is reached on this matter. However, the information already collected is very useful in giving insight on how the material will perform throughout the process. This topic is very interesting but it's out of the scope of this work.

1.4. Forming Machinery

To perform Single Point Incremental Forming there are a few indispensable requirements. One of them is the need for a CNC-controlled three axis machines. Currently there are two ways to produce parts using Single Point Incremental Forming, dedicated and adapted machines. Dedicated machines may vary in type, but there are only a few models available, mainly because this is a recent technology and there are only a few companies that will invest in developing a SPIF machine. So the most common is the use of adapted machinery. The characteristics that have to be accounted for SPIF work are speed, working volume, stiffness and load force. High speeds, large working volumes, sufficient stiffness and high load capacity are favorable. Accordingly to Jeswiet et al. [2] the types of machines that can be use to do incremental forming are:

- CNC milling machines;
- Robots;
- Purpose built machines;
- Stewart platforms and Hexapods.

1.4.1 CNC milling machines

The more common in SPIF process is the use of three-axis CNC-controlled milling machines, which are adapted for the process (Figure 10) [7], [28-31]. According to Allwood et al. [9] these machines are very attractive “because of the low additional costs of beginning operation”. Unfortunately they also have some disadvantages; firstly because “milling machines are generally not designed for high loads normal to the spindle, there is a danger that the machine will be damaged during incremental sheet forming operations”, (Blue area, Figure 10). Therefore, the use of these systems is limited to softer materials, such as aluminum alloys, that normally involves forces applied to the tool much smaller than the forces needed for other materials, such as steel. Secondly, “CNC machines do not generally provide instrumentation for measurement of three-axis forces at the tool tip”. Third reason is that “the worktable of a CNC machine is generally solid and has limited width, so there is limited access to the reverse side of the workpiece”, and also limits the work volume, (Red area, Figure 10).

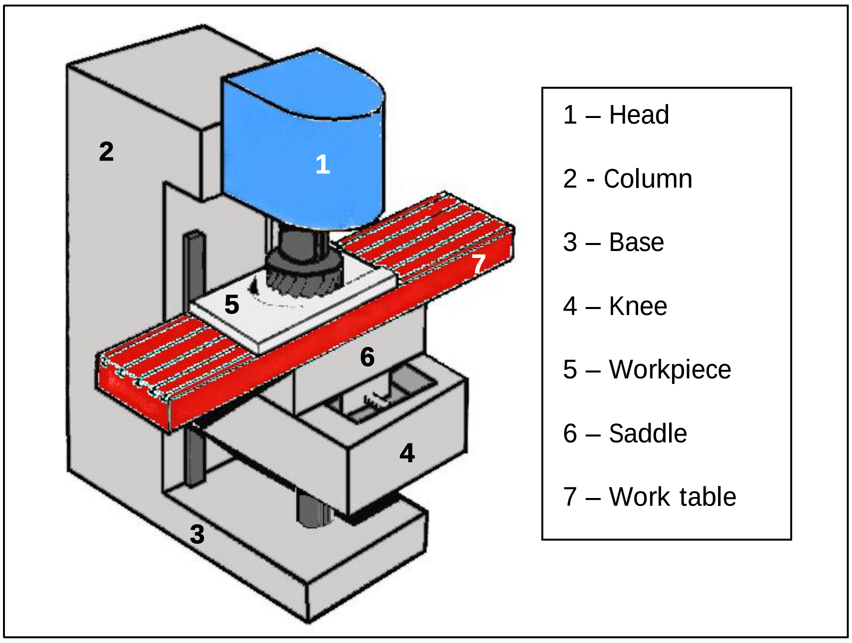


Figure 10 - Milling machine.

Since the simulation of SPIF process is complex and the time required to complete a simulation is currently many times greater than the times required to form the product, “high accuracy forming will only be achieved either by repeated trials of tool paths with correction based on errors in the finished form or by use of some form of on-line shape measurement and feedback control via an algorithm to modify the tool path” [9]. Examples of SPIF adapted milling machines can be seen in Figure 11.

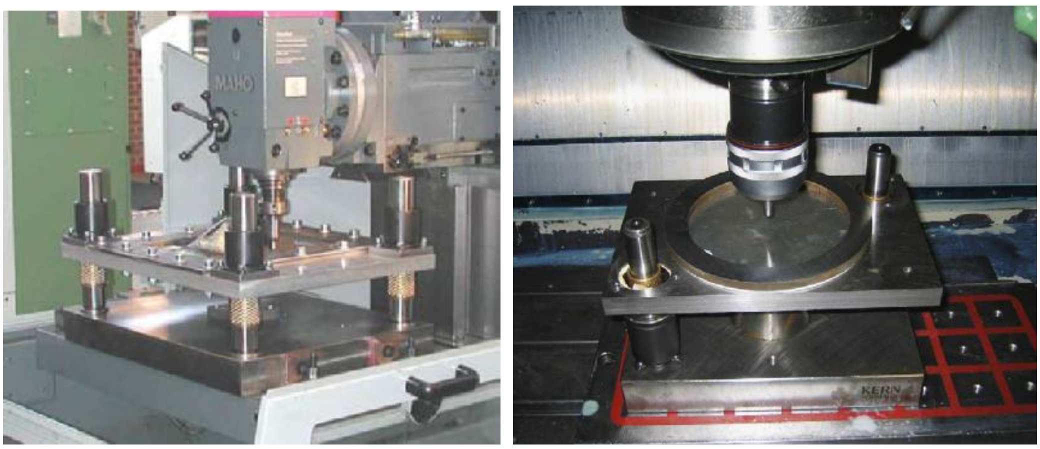


Figure 11 - SPIF adapted milling machines. (Left, Jeswiet et al. [2]), (right, Kopac et al. [31]).

1.4.2 Robots

Another technology that has been used/adapted in SPIF has been the robots with serial kinematics (Figure 12) [32-34]. These systems are attractive because they have high flexibility and mobility which enables the manufacture of parts with high complexity and work at high speeds. The final position of the tool is the result of the combination of the different joint movements, which can occur at the same time. Another advantage is that they allow the tool to operate in the best angle configuration. This is an important aspect when dealing with complex shapes because it allows to nullify efforts that otherwise would be hazardous to the tool, and to the machine itself. It also prevents the degradation of the metal sheet and improves accessibility.

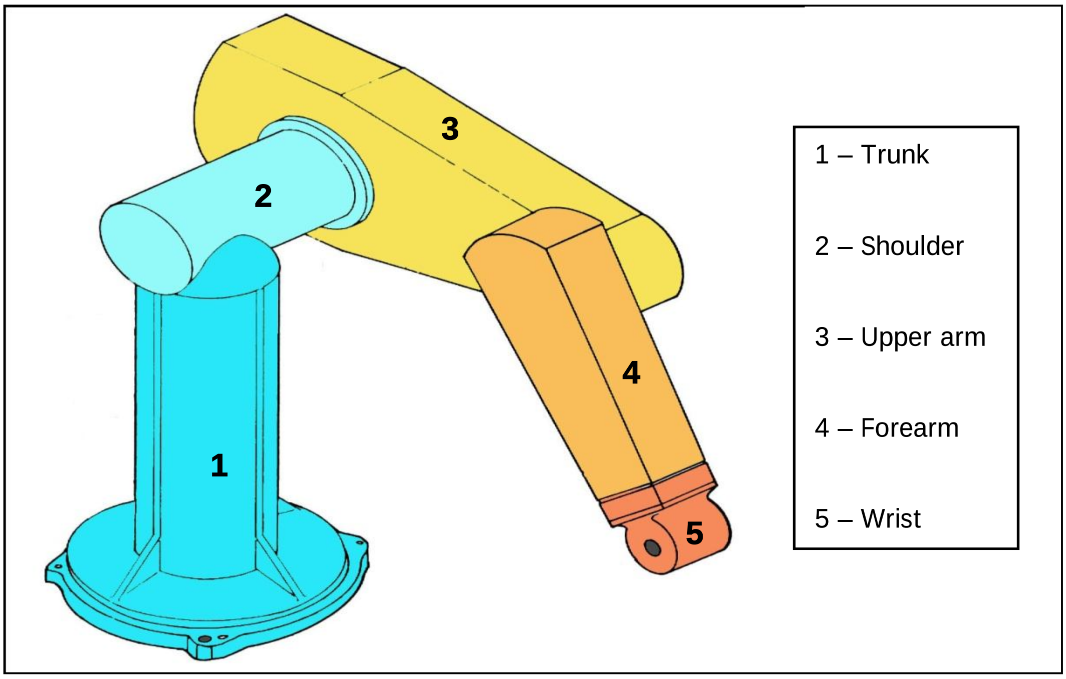


Figure 12 - Articulated robot arm.

The disadvantages, just like the milling machines, are that they have low stiffness and low admissible forces at the tip of the tools. Therefore, the use of these machines is limited to softer materials or else they would require investment in stiffening the joints. Another disadvantage is the lower precision. Because it's a serial configuration, the positioning errors of the individual axes tend to sum and this result in higher geometric errors when comparing with other machines. An example of these systems can be seen in Figure 13.

Figure 13 - Robot performing Single Point Incremental Forming [6].

1.4.3 Purpose built machines

The purpose built or dedicated machines, unlike adapted machines, are designed for incremental forming process, and try to have simultaneously high rigidity and high flexibility. These systems allow the manufacturing of parts with complex geometries, while maintaining high accuracy and good surface finish. There are very few models on the market, and a few currently being studied and proposed.

1.4.3.1 Dieless NC Machine

Dieless NC Machine is a technology developed by a Japanese company named Amino Corporation [35]. They have developed a series of commercial models that work with the Single Point Incremental Forming principle. There is not much information (nor scientific research) about their machines, except the one found on their website. Their technology is based on a complete package that allows going straight from data to finished metal parts with only minimal soft tooling. According to the information available, the Dieless NC Machine can use a wide variety of materials, including mild steels, aluminum, titanium and even perforated steel mesh, with thickness ranging from 0.1 mm to 4.0 mm, depending on the model. The Dieless NC machine can be seen in Figure 14.

Figure 14 - Amino's Corporation, Dieless NC machine [35].

Amino Corporation offers standard sized models of their Dieless NC Machine. Two of the models, DLNC-RA and DLNC-RB, are designated as research-use and have smaller tables and slower in-table traverse speeds. The other 4 models, DLNC-PA, DLNC-PB, DLNC-PC and DLNC-PD, are primarily designed for industrial use. The specifications for all the models are shown in Table 6.

Table 6 - Amino's Corporation models of the Dieless NC machine [35].

		DLNC-RA	DLNC-RB	DLNC-PA	DLNC-PB	DLNC-PC	DLNC-PD
Max. blank size (mm)		400x400	600x600	1100x900	1600x1300	2100x1450	2600x1830
Max. forming size (mm)		300x300	500x500	1000x800	1500x1200	2000x1300	2500x1750
Max. forming depth (mm)		150	250	300	400	500	600
Stroke (mm)	X axis	330	550	1100	1600	2100	2600
	Y axis	330	550	900	1300	1450	1900
	Z axis	200	300	350	450	550	650
Max. work holder size (mm)		700x750	1000x950	1300x1100	1800x1500	2300x1650	2800x2030
Forming capacity thickness (mm)	Steel (CR)	0.6~1.6	0.6~1.6	0.6~2.3	0.6~3.2	0.6~3.2	0.6~3.2
	Stainless	0.5~1.0	0.5~1.0	0.5~1.5	0.5~2.0	0.5~2.0	0.5~2.0
	Aluminum	0.5~3.0	0.5~3.0	0.5~4.0	0.5~5.0	0.5~5.0	0.5~5.0
Forming speed (m/min)	X, Y axis	30.0	30.0	60.0	60.0	60.0	60.0
	Z axis	310.0	10.0	10.0	10.0	10.0	10.0
AC servo motor power (kW)	X axis	0.9	1.4	5.9	8.2	10.0	16.0
	Y axis	0.9	1.4	4.5	4.5	4.5	7.0
	Z axis	0.9	0.9	1.0	1.0	1.0	3.0
Machine weight (ton)		3.0	5.0	6.0	8.0	10.0	(18)

In terms of operation, Dieless NC forming is very similar to NC mills and machining centers. Simple to use software translates data directly into G-code tool paths. After having the G-code downloaded and being zeroed, the Dieless NC Machine then operates fully hands-free. As the spindle completes its path, the blank is lowered further over the fixture ready for the spindle to make another pass, continuing until the final shape is achieved. The volume of production can vary from a single piece, up to 500 pieces per month. The Dieless NC machine can even finish and assemble the part, performing actions such as trimming, bending and hemming.

1.4.3.2 Cambridge ISF

In 2004, at Cambridge University, the Cambridge ISF [9] was developed with the objective of performing SPIF operations (Figure 15).

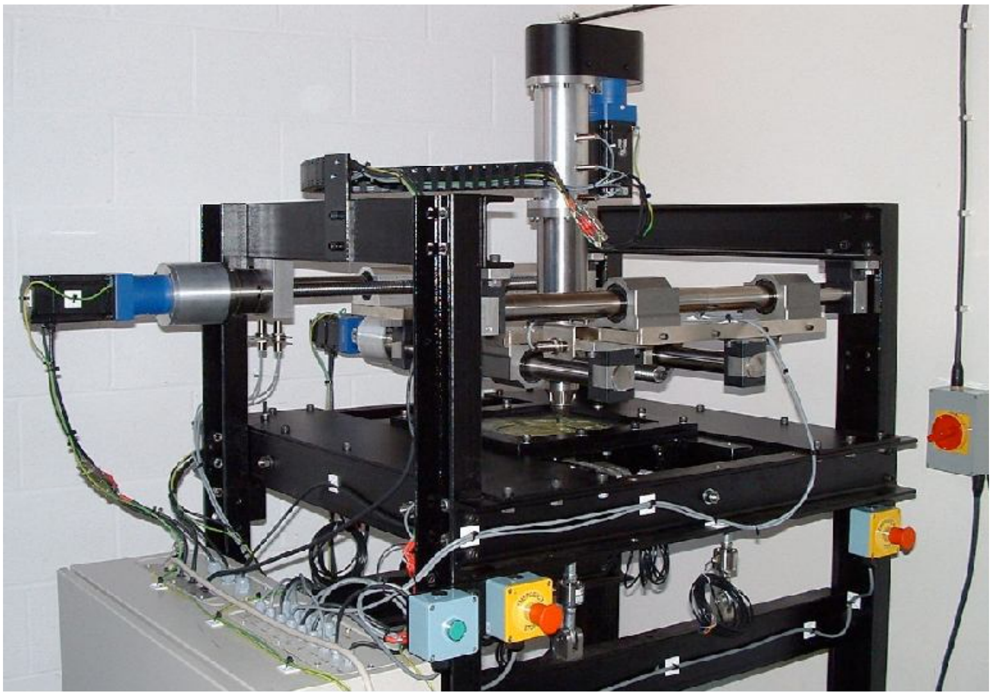


Figure 15 - Cambridge ISF Machine [9].

According to Allwood et al. [9], the development of this machine was centered on the distinctive requirement to maintain sufficient accuracy while in the presence of high horizontal and vertical tool forces. With that intent and to “avoid excessive moment loads on any of the bearing in the system, the vertical axis was maintained as close to the workpiece as possible. Vertical motion is controlled by a ball screw with a nut fixed to the tool shaft. The x and y axes are formed from two parallel hardened steel shafts, and are driven by ballscrews with co-axially mounted servo-motors driving the shaft via a planetary gearbox". The rotation of the tool is freely sustained by bearings. A one-to-one gear drive is used to allow the motor to sit parallel to the main shaft. "Vertical motion is provided by a 750 W motor through a 15:1 planetary gearbox, which with a motor torque of 2.4 Nm and an estimated system efficiency of 70%, provides a maximum vertical force of 26.4 kN". The specifications of the Cambridge ISF are summarized in Table 7.

Table 7 - Machine specifications.

Parameter	Measurement
Workpiece (active area)	300 x 300 [mm]
Material	Up to 1,6 [mm] mild steel
Vertical force	<13 (work), >26 (max) [kN]
Horizontal force	<6,5 [kN]
Tool tip speed	<40 [mm/s]
Tool tip radius	5, 10, 15 [mm]
Maximum cone angle	67,5°
Maximum vertical axis travel	100 [mm]

The workpiece is held in a channel section frame, and may be clamped over a backing plate. The frame is mounted on six 10 kN load cells organized to provide a 6 degree-of freedom constraint without any moment loads on the load cells [9].

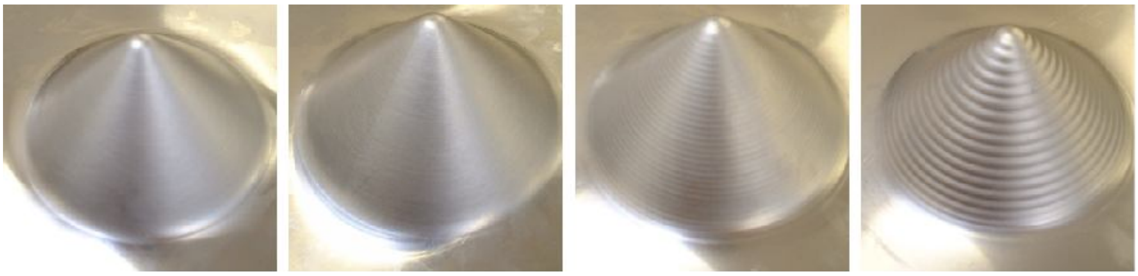


Figure 16 - A cone produced by the Cambridge ISF with varying step sizes. From left to right, 0.2 [mm], 1 [mm], 2 [mm], 4 [mm], [9].

1.4.3.3 Tricept HP1

According to Callegari et al. [36] the Tricept HP1 is a hybrid machine that uses a spherical wrist with serial kinematics (Roll-Pitch-Roll) mounted on a mobile platform with parallel kinematics. It can handle six degrees of freedom. The apparatus of the Tricept HP1 can be seen in Figure 17.

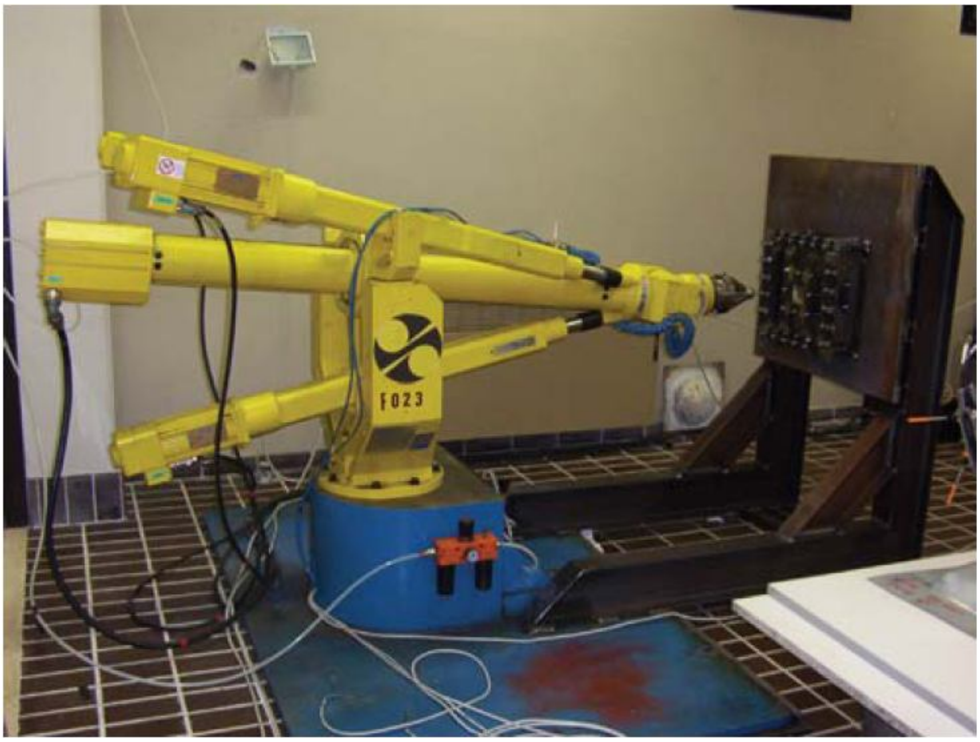


Figure 17 - The hybrid robot Tricept HP1, [36].

Callegari et al. [36] defined this machine as having a predominantly parallel nature. That allowed high stiffness, good accuracy, and fine repeatability levels, even under heavy loads. Callegari et al. [36] also explained that the stresses placed on it are transferred to the robot chassis using the three legs, which are mainly loaded with normal stresses. Also, positioning errors of the individual axes tend to counterbalance, rather than summing as in the case of serial configurations. The structure of the Tricept HP1 is built with a thick metal sheet to ensure stiffness, and allows both the robot as the supporting frame where the blankholder is mounted to be held down. The robot can apply a maximum thrust of *15 kN* within an area of *2000 mm x 600 mm*, with a repeatability better than *0.03 mm*. The forming tool is held by a pneumatic gripper that subsequently is attached to the robot flange. The blankholder and the blank are held together by an array of bolts.

Callegari et al. [36] described that the drawbacks of this machine reside mainly in the workspace's complex shape do to its limited agility (Figure 18). Therefore, a simulation tool was implemented in order to allow the machine kinematics off-line analyses and evaluate beforehand the viability of a certain task.

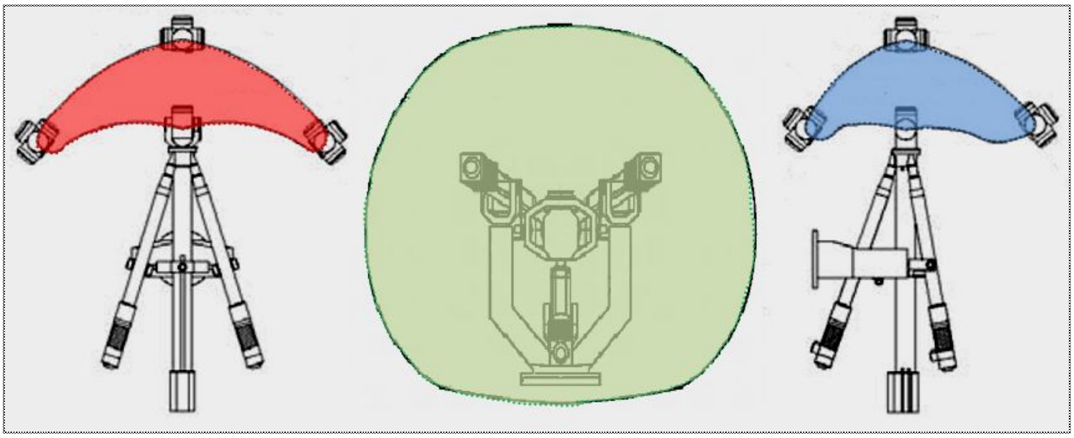


Figure 18 - Tricept HP1 workspace's shape. Top view, (left), front view (middle), side view (right), [36].

Chapter 2

2.1. Motivation

Single Point Incremental Forming is in its early years. The means to perform this forming process are still very limited and rudimentary and there is not a satisfactory implementation level in the industry.

In order to make a positive contribution to the development of this industry and to the process itself, a new machine is being developed at the University of Aveiro intending to take the potential of this process to the highest level. The project for such machine was initiated in 2010 in the work of Marabuto [8]. In this work there will be a resume of the previous work and the continuation of the development.

This machine brings a new approach to the SPIF industry. As presented in chapter 1 (section 4), the machinery used to perform SPIF operations has limitations in their work volume with limited movements and in the magnitude of applicable forces. With that in mind, this machine was projected to overcome that obstacle, and was provided with a system with 6 degrees of freedom, while maintaining the ability to apply high loads. The disadvantage is the increase in volume occupied by the kinematic system.

This project and consequently the machine have received the name of SPIF-A. SPIF stands for Single Point Incremental Forming and the A stands for Aveiro, since this project is being carried out at the Department of Mechanical Engineering of Aveiro.

This machine applies different technologies that need to be adapted and connected together. In this work, several fields were studied like, redesign of the kinematic system, redesign of the structure and its positioning system, development of the hydraulic system, development of the electrical system, development of the force measuring system, and minor changes in the spindle project.

This project aims to enlarge the doors to future research and development of the process, both in improving the machine but also in developing and understanding the forming mechanism.

2.2. Reading Guide

This thesis is divided in three chapters. The first one involves the definition of the process and the detailed description of the different parameters that define the process. Also it contains the state of art regarding the machinery used to perform SPIF operations.

The second chapter is focused on the project of SPIF-A. This chapter contains a resume of some previous work and some modifications done in those areas, and also describes the work developed during this year.

At last, the third chapter presents some conclusions that can be taken from the work done and also the description of some aspects that still need to be developed.

2.3. Main Characteristics of SPIF-A Project

2.3.1 Kinematic System

In order to achieve a machine capable of accurately and quickly perform all the operations associated with the SPIF process, it was required that SPIF-A was equipped with linear and rotational movements in the tree directions. In order to achieve that feature, it was necessary to make an analysis of the kinematic systems existent on the market. After a careful evaluation the chosen configuration was the Stewart platform kinematic system, as addressed by Marabuto [37]. This system consists mainly of two platforms coupled together by six parallel linear actuators driven by electrical drives such as servomotors or fluid power drives such as hydraulic or pneumatic systems. The motion of one platform with respect to the other can be produced by shortening or extending the actuator lengths. Stewart platform-based manipulators can have several variations as shown in the figure below. These variations consist in changing the type and number of joints between the linear actuators and the two platforms.

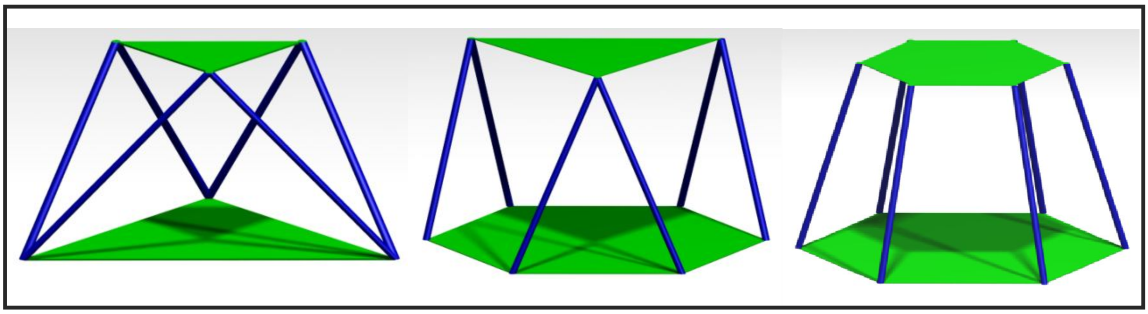


Figure 19 - Different variations of Stewart’s platform, 3 by 3 (left), 6 by 3 (middle), 6 by 6 (right).

The selected variant was 6 by 6, that represents six connections in each platform, because it’s the one that offers a better load distribution, also it allows the use of simple universal joints.

2.3.1.1 Actuators

The dimensioning and choosing of the necessary actuators is addressed in the hydraulic section.

2.3.1.2 Joints

For the Stewart platform to execute movements the actuators must have two degrees of freedom at each joint. To ensure that the connections between the actuators and the platforms have those degrees of freedom the use of universal joints were considered. The first approach taken was to project and manufacture the joints within the University, but due to its effective construction cost being too high that idea was abandoned. So it was decided to search companies with standard models that fitted the necessary factors [8]. After consulting the available catalogs, the joints chosen were from Rotar [38], an Italian company specialized in universal joints. The joints are built in Stainless Steel X_5CrNi_{1810}. The joint can be seen in the following figure.

Figure 20 – Photo of the chosen joints.

2.3.1.3 Platform bases

The bases of the Stewart platform were redesign to be lighter, but at the same time endure the forces and moments that result from the machine operation. The material selected was duraluminium. This material allows a decrease in weight when compared with steel while maintaining the necessary durability.

The fixed platform was designed to have the minimum possible weight while maintaining the necessary geometry to implement the holes for screwing the universal joints and the connection to the structure. The actuators were distributed in three pairs with an angular spacing of 120 degrees. Also the pairs have a spacing of 200 mm between each actuator (Figure 21). This arrangement permits a 6 by 6 configuration, while including some of the 3 by 3 properties.

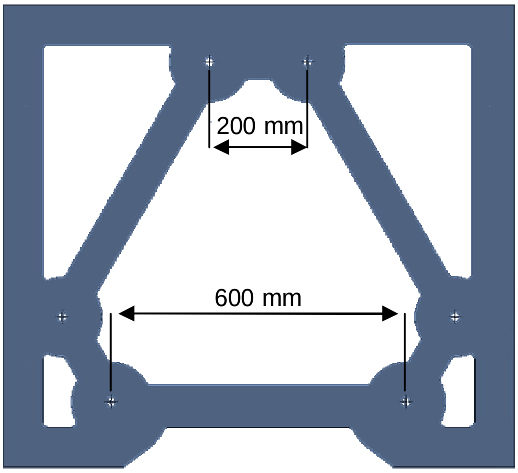


Figure 21 – Distribution of the actuators connections in the fixed platform.

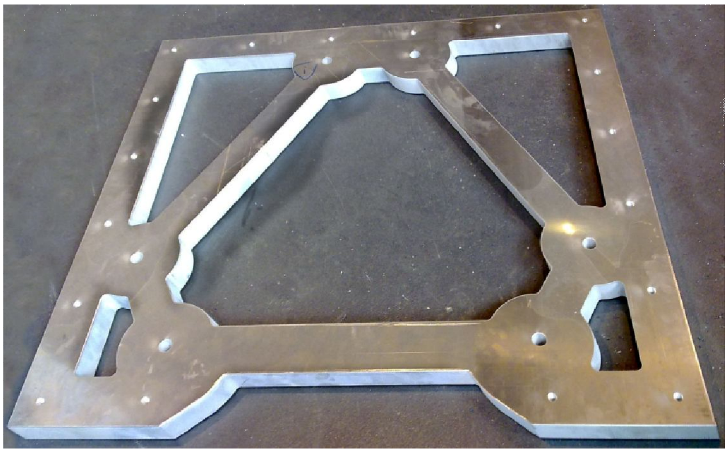


Figure 22 - Fixed platform.

The movable platform was design to accommodate the spindle and the force measuring system. In order for a proper maintenance and accessibility to the systems mentioned three slots were added, resulting in reducing the weight.

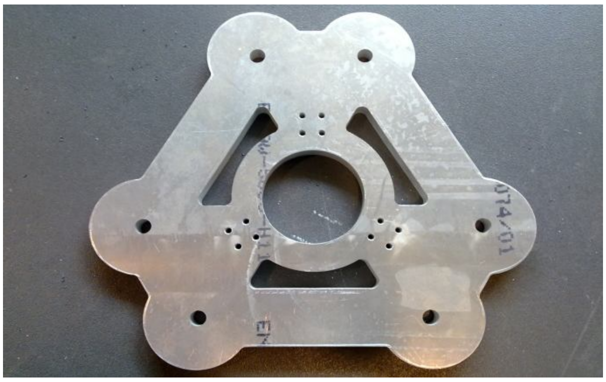


Figure 23 - Movable platform.

2.3.1.4 Movements range of SPIF-A

The range of the Stewart platform was determined by using an algorithm that simulated the maximum displacement of the actuators in all directions [39]. This algorithm was developed to determinate the overall dimension of the structure and have an estimation of an acceptable displacement of the actuators. The software used was Matlab from Mathworks Inc. and the approximated obtained area was around 1200 by 1200 mm. The following figure shows the plot of the results obtained with the algorithm.

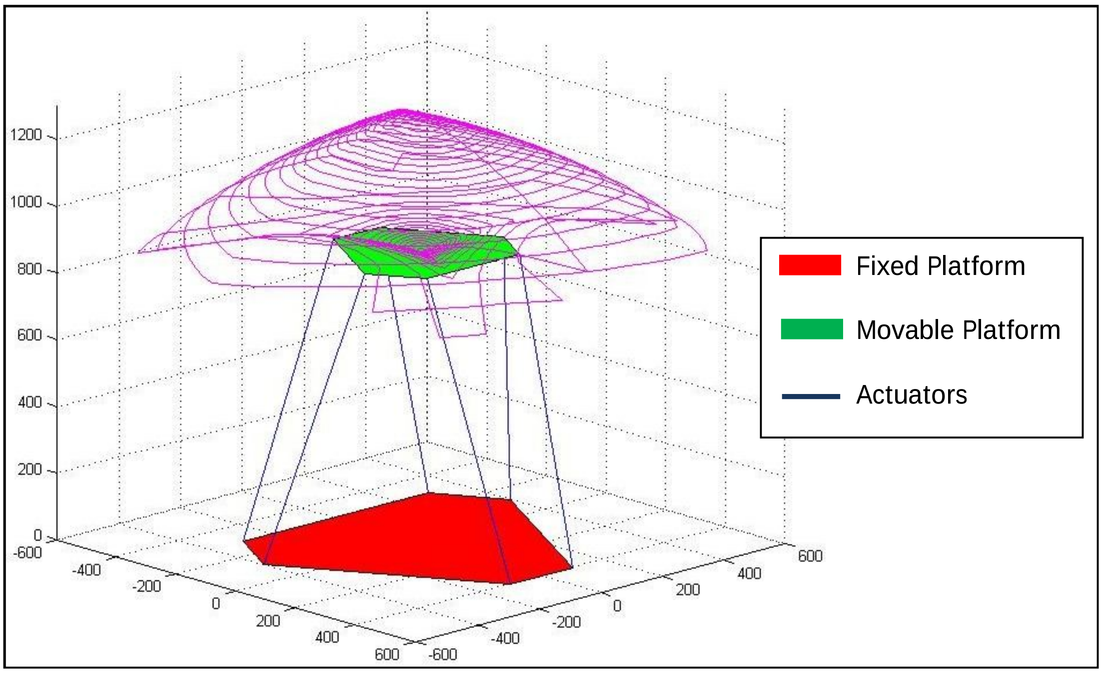


Figure 24 - Graphic with the range of the Stewart platform [39].

An overall of SPIF-A kinematic system can be seen in the following figure. This design results in a kinematic system with high precision while allowing the appliance of high loads.

Figure 25 - Stewart Platform overall.

2.3.2 Spindle Development

For the SPIF process the most advantageous solution for the interaction between tool and metal sheet is for the tool to roll over the blank with free rotation and with low friction [8], [26], [28], [37]. In order to allow that feature, a custom spindle had to be developed.

The spindle consists of a mechanism that allows selection and control of the forming tool and its free rotation. Also, the spindle must be capable of withstand the forces that are developed during the process and drive them to the machine structure. The project of a spindle must account for situations where the part geometry doesn´t allow for the forming tool to maintain a normal position with the surface of the metal sheet (Figure 26), resulting in occurrence of tangential forces that must be withstand.

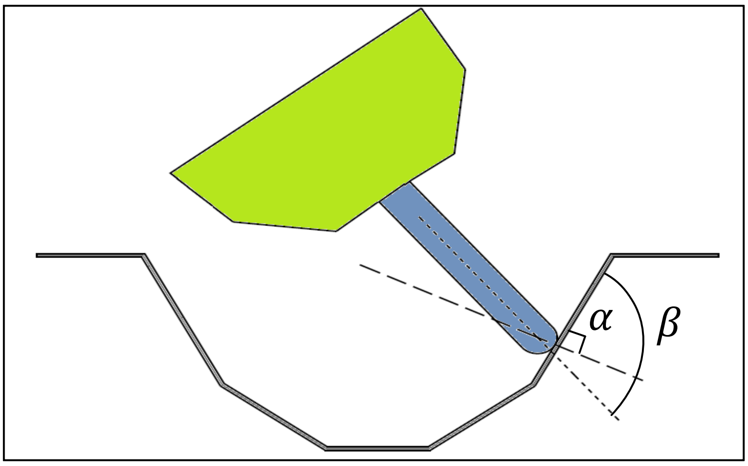


Figure 26 - Ideal angle of formation (α), possible angle of formation (β).

As defined by Marabuto [8] the spindle developed for the SPIF-A project was designed to be a compact construction, allowing it to be robust, but maintaining flexibility and accessibility to the work piece. The spindle project was divided into three main components: the shaft that connects to the tool holder, the exterior casing that houses the shaft and connects the spindle to the force measuring system (this component suffered a redesign), and bearings to ensure proper support and positioning of the shaft. The technical drawing can be seen in the Appendix.

2.3.2.1 Tool holder

The criteria for selecting a tool holder include the versatility and capacity to withstand the forces and moments during the process. In the case of SPIF, with the wide range of diameters of tools used, the tool holder must have the capacity of housing tools with diameters of 5 to 30 mm. The tool holder was chosen according to DIN 2080, allowing the shaft to be shorter and with less bending. Figure 27 shows the detail of the clamping system [8].

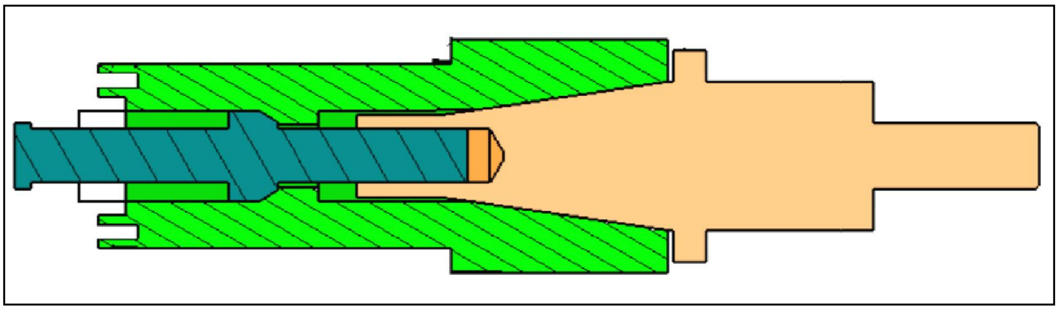


Figure 27 – Clamping System [8].

2.3.2.2 Shaft

The material chosen for the shaft was a quenched and tempered steel alloy of high strength, 3OCrNiMoS. To evaluate the reliability of the shaft, a structural and fatigue analysis was performed, and the results are resumed in table below. From this analysis it was concluded that the shaft is capable of withstanding the forces and moments that it will be subjected [8].

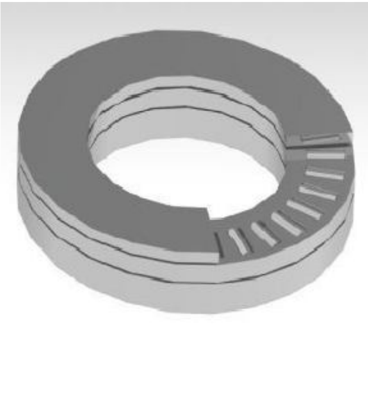
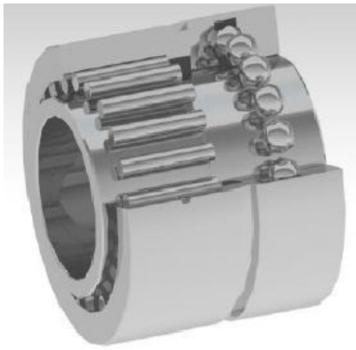
Table 8 - Results of the shafts analyses [8].

M_z	θ_{max}	δ_{max}
43,33 Nm	1,045 × 10^{-2} $mrad$	6,672 × 10^{-1} mm

2.3.2.3 Bearings

The selection of the bearings followed three criterions: the right position of the shaft in the casing, low level of misalignment and vibrations, high capacity to undertake the forces developed during process [8]. Table 9 presents the chosen bearings.

Table 9 - Selected bearings [8].

Type of bearing and Characteristics	A	B	C
	Axial Needle Bearing	Needle combined with ball bearing	Ball Bearing
			
	Resist compression loads	Resists to bending and compression loads	Resists to bending loads

To determine the most stable configuration, tests with various arrangements were performed. Figures 28 show one of the arrangements that were tested [8].

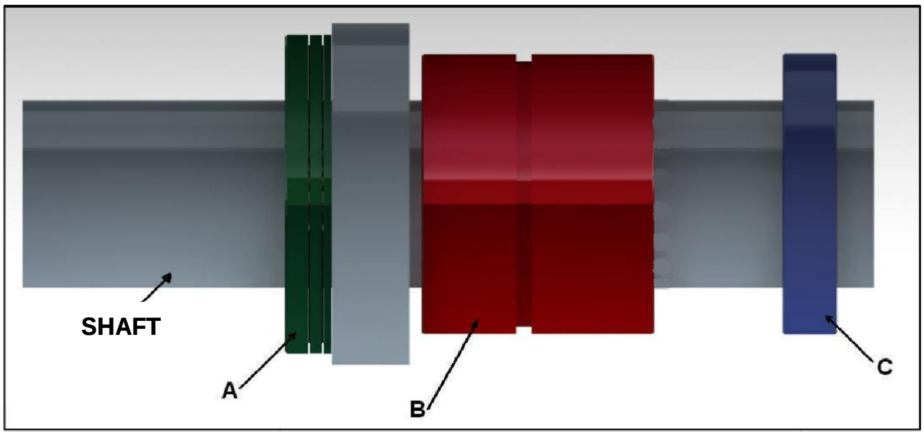


Figure 28 – Configuration tested [8].

Figure 29 shows the exploded view for the final version of the spindle, including the components described above and the redesign of the exterior casing to accommodate the force measuring system.

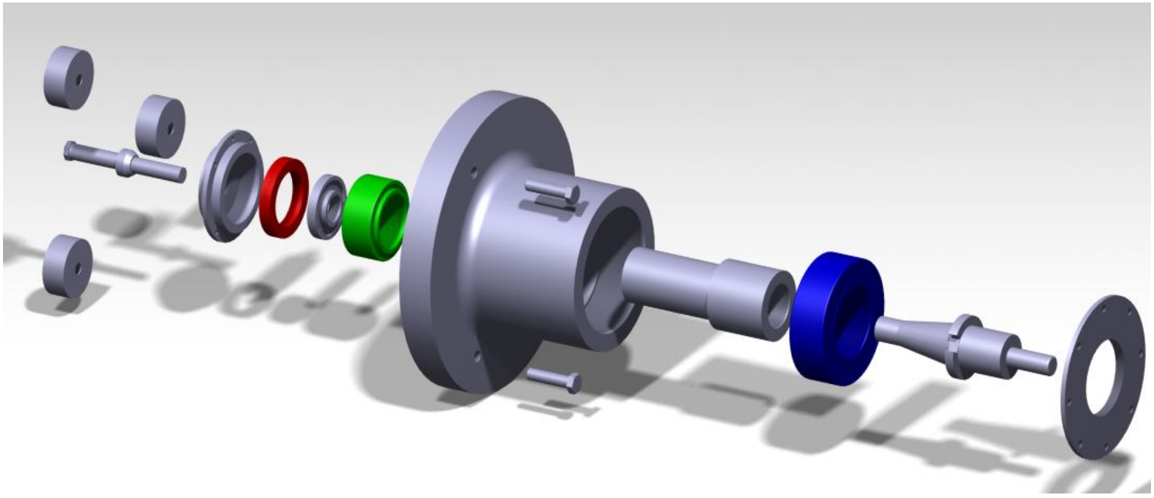


Figure 29 – Exploded view of the final configuration of the spindle.

2.3.3 Hydraulic System

Hydraulic power systems and actuators are a very common technology and have been used for a long time in a wide range of industrial applications. The main advantage is the ability to carry out work with high loads or develop large forces while being a relatively inexpensive power source. Due to the advance of present technology, hydraulic systems can be utilized in processes that require a high level of precision. This is possible due to the implementation of computer controlled solutions with motion and/or force control.

This section presents the design of the hydraulic system applied in the Stewart platform, as present on the SPIF-A. It also presents the selection of the different equipment needed and design of the hydraulic circuit.

2.3.3.1 Hydraulic actuators

Electro-hydraulic actuators with double effect were chosen for the Stewart platform. These were acquired from Parker Hannifin Corporation [39] and their choice was based on the following parameters:

- Work Pressure (above 100 *bar*)
- Minimum Stroke (400 *mm*)
- Force (resultant of: 13 *kN* normal; 6,5 *kN* tangential)

Although the Stewart platform is composed by six actuators, not always all of them are subjected to the same resisting reaction of the metal sheet, depending directly on kinematics of the system. The minimum area, required to obtain the desired forces in at least one actuator, can be found with Equation 5.

$$P = \frac{F}{A} \Leftrightarrow A = \frac{\sqrt{(13 \times 10^3)^2 + (6.5 \times 10^3)^2}}{100 \times 10^5} = 0.00145\, m^2 \qquad (5)$$

where,

P – Working pressure;

F – Maximum necessary force for the process;

A – Minimum area of the actuators.

The minimum diameter could then be obtained by

$$A = \frac{\pi}{4} \cdot d^2 \Leftrightarrow d = 0.043\, m \quad (6)$$

Having all the necessary parameters in place, the project moved to the selection of the most appropriate model. The chosen actuators were from the series HMIX cylinder with Integrated Transducers and low friction hydrodynamic seals to improve dynamic performance. The characteristics are summarized in Table 10. Figure 30 shows the purchased cylinder[1].

Table 10 - HMIX cylinder characteristics.

Characteristic	Value
Stroke	400 mm
Bore Diameter	63 mm
Rod Diameter	45 mm
Maximum work pressure	210 bar

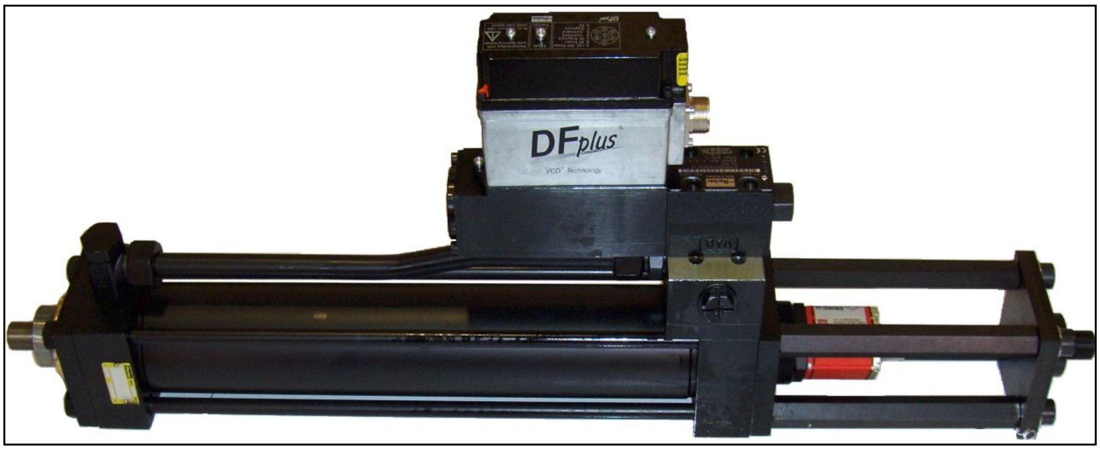


Figure 30 – Photo of the cylinder used in SPIF-A.

[1] Sponsoring from Parker-Hannifin is greatly acknowledged.

2.3.3.2 Hydraulic Pump

In order to determine the best suitable pump to feed the overall system, the total flow rate must be calculated. That can be determined using the characteristics of the actuators shown on Table 10 and the required velocity. For a maximum velocity of 0.05 m/s the flow rate is given by equation (7).

$$\dot{m} = v \cdot A_1 = 0.05 \times {}^{\pi}/_{4} \cdot {d_{Bore}}^2 \cong 56\ l/min \qquad (7)$$

where,

$\dot{m}$ – Flow rate required
v – Velocity of the actuators
A_1 – Area under pressure inside the cylinder

Using a standard rotation for industrial pumps of 1500 rpm and using equation (8) the pump's displacement can be estimated. This assessment serves just has an evaluation because the displacement of a pump varies with its type.

$$D = \frac{n_c \cdot \dot{m}_c}{n_{rpm}} \Leftrightarrow D = 37.5\ cc \qquad (8)$$

where,

D – Pump displacement
n_c – Number of cylinders
$\dot{m}_c$ – Flow per cylinders
n_{rpm} – Rotations per minute

Knowing the required flow rate to feed the system and an estimation of the necessary pump's displacement, once again the search for the best equipment took place. The speed of the actuators is variable, so in order to maintain a steady flow and pressure, the best solution is a variable displacement vane pump. The selection was made from a list of models from the Bosch – Rexroth Company [40]. The chosen model was PV7 – 40-45 and its characteristics can be seen in Table 11.

Table 11 – SPIF-A's pump characteristics.

Model	PV7
Displacement	45 cc
Flow	66 l/m
Maximum pressure	160 bar

2.3.3.3 Hydraulic Circuit

In order to distribute, control and maintain the flow from the pump to the cylinders a hydraulic circuit was designed. The overall of the circuit can be seen in Figure 31. The circuit contains an accumulator in order to counteract the sudden change in pressure, a pressure relief valve and a discharge mechanism. Also, the reservoir was dimensioned to, in case of rupture of a distribution tube, there is enough time to shutdown the pump before it runs out of fluid and results in its permanent damage. Also the reservoir must have enough capacity so that the fluid can cool down before it returns to the pump again. If the fluid becomes too hot is viscous properties will change and that could result also in the damage of the pump or other equipment. The characteristics of the accumulator and the reservoir can be seen in Table 12.

Table 12 – Accumulator and reservoir characteristics.

Equipment	Maker	Characteristics	
Reservoir	Vescor	Capacity 80 liters	DIN Type Style 1
Accumulator	Bosh Rexroth	Capacity 2 liters	Flow 60 l/min

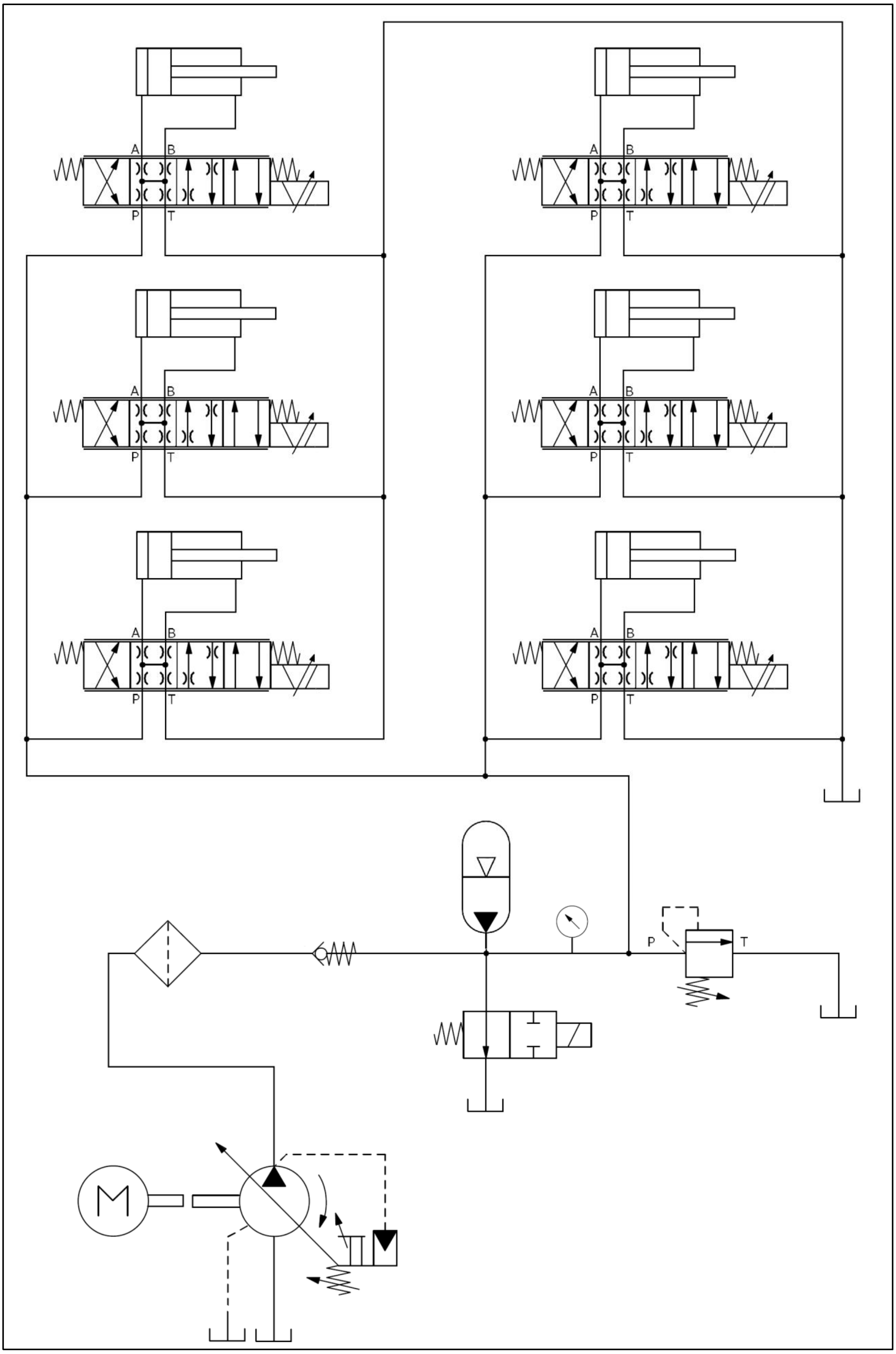


Figure 31 – Hydraulic circuit of SPIF-A.

2.3.4 Electric System

Electricity is a well known source of power that sometimes has its potential hazards left without thought. In order to prevent that someone gets subjected to dangers such as electric shock, electrocution, fires and explosions, all machinery must be dealt by qualified people and its design and maintenance must follow safety protocols.

SPIF-A is a machine that requires the use of different types of electric power, such as Alternating Current (AC) and Direct Current (DC). Also it requires the use of electrical equipment that must receive maintenance from time to time. The electrical plan of SPIF-A was fully developed with that in mind, and can be found in the Appendix. The power input of the major electrical components of SPIF-A can be seen in Figure 32 and a list of the different material necessary for the electrical system can be found in Table 13.

Table 13 – List of electrical material and equipment necessary.

Component	Characteristics	Qt.
Disconnect switch	194E-E25-1753	1
DC Linear Power Supply	In 85-264 V AC – Out 24 V DC 2,5 A	1
DC Switching Mode Power Supply	In 180-264 V AC - Out 24 VDC 20 A	1
Switch	3A 2P	3
Load cells	In 24 V DC – Out ±10 V	3
Signal Amplifiers	18-28 V DC 70 mA	9
220 V Outlet	IP44 16A 2P + T	1
Fuses	4.0 A 50	6
Electrical Cabinet	600 x 600 x 210	1

The electrical system is compose of four major parts, the 220 V outlet to supply the equipment external to the machine, the power supply for the motor that drives the hydraulic pump, and two DC power suppliers for the amplifiers, the sensors and the servo solenoid valves. Since the servo solenoid valves require much higher currents and sudden changes of the power supply, to prevent the introduction of noise into the sensors signals, these systems must be separated.

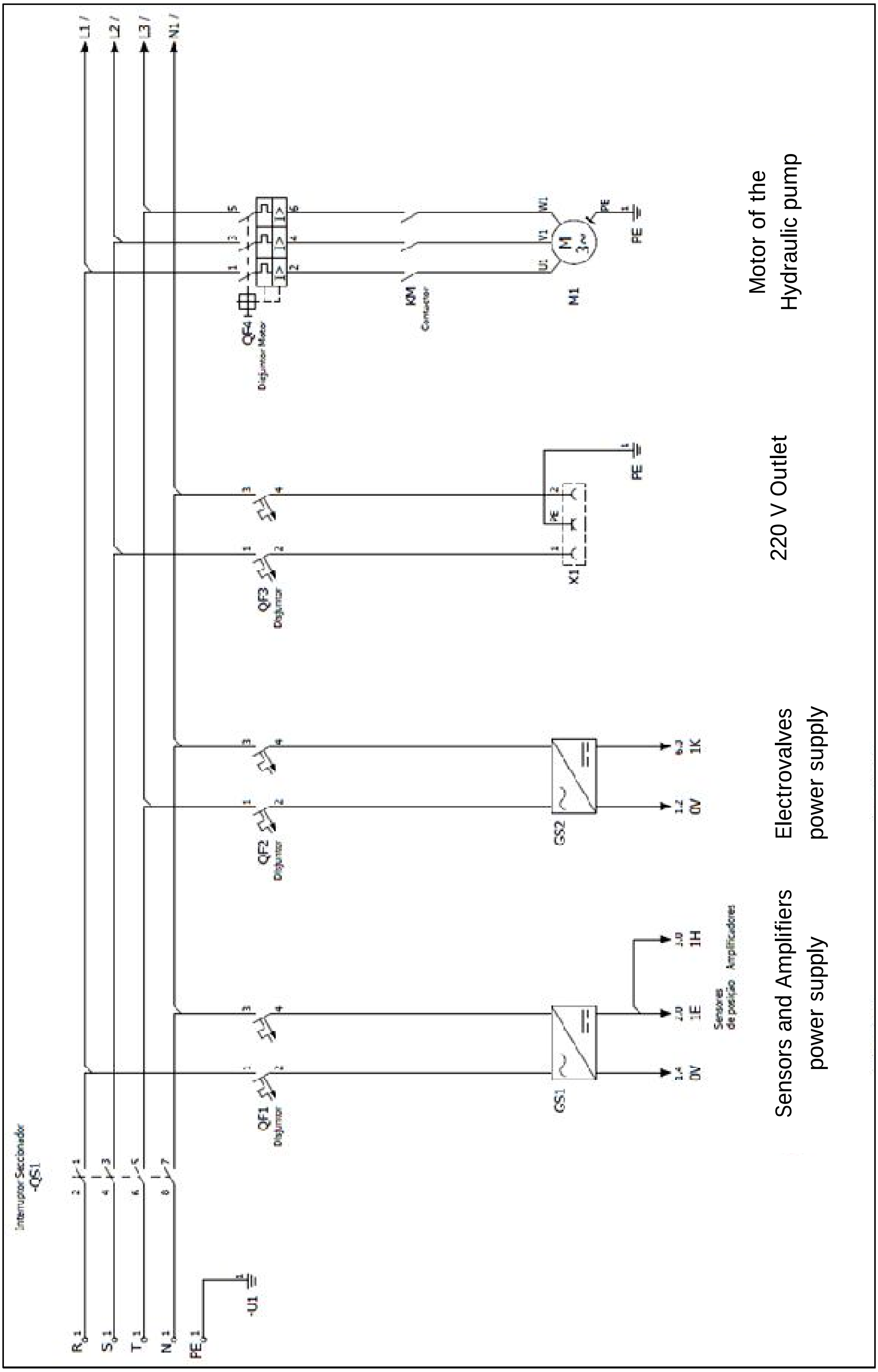


Figure 32 – Power input.

2.3.5 Force measuring system

In order to do a proper control of the forming operation, it is necessary to have a feedback of the applied forces. To do so with adequate precision, load cells were selected.

Load cells can be distinguished according to the type of output signal generated (pneumatic, hydraulic or electric) or according to the nature of the perceived forces (bending, shearing, compression, traction). For this project, there were selected electric load cells. These allow conversion of forces into electrical signals. The maximum forces to be measured were 13kN tensile/compression and 6.5 kN shear.

In order to get a compact, robust, but not expensive solution, three-dimensional load cells were chosen from an American company named Michigan Scientific Corporation [41]. These load cells were projected to experience compression/traction while supporting lateral/shear forces, however, do not support high moments. To minimize reading errors and enhance stability three load cells were used and mounted on the same plane with angular spacing of 120 degrees. This also allows the reading of bending moments. The distribution of the forces and moments can be understood by analyzing the left side of Figure 33.

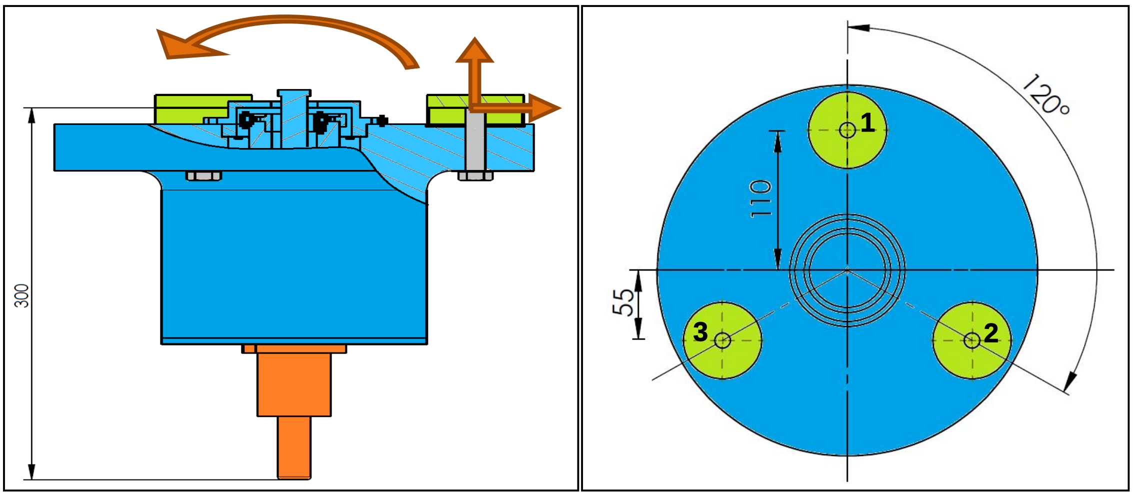


Figure 33 – Applied force to the tool and transition to the load cells (left), arrangement of the load cells (right).

2.3.5.1 Forces applied to the load cells

For a correct choice of the load cell capacity to implement, a study of the forces and moments acting on the system is necessary.

- Horizontal force

$$\sum F_x = 0 \tag{9}$$

$$F_{xpunção} - F_{xLC1} - F_{xLC2} - F_{xLC3} = 0$$

$$F_{xLC1} = F_{xLC2} = F_{xLC3}$$

$$F_{xLC1} \approx 2.2\ kN$$

- Vertical forces (without moment)

$$\sum F_z = 0 \tag{10}$$

$$F_{ztool} - F_{zLC1} - F_{zLC2} - F_{zLC3} = 0$$

$$F_{zLC1} = F_{zLC2} = F_{zLC3}$$

$$F_{zLC1} = 4{,}5\ kN$$

- Moments

To study the moments generated in the force measuring system is necessary to know the length of the lever arm involved and the distance from the force to the point of application. That can be seen in the right side of Figure 33.

- Moment created by shear force on the tool

$$M_{tool} = 6{,}5 \times 10^3 \cdot 0{,}3 = 1950\ Nm \tag{11}$$

Distance from the tip of the tool to the mid plane of the load cell = 300 mm

- Resulting moment on load cells

Distance to the farthest load cell (Figure 33, load cell 1) = 110 mm

Distance to the remaining load cells (Figure 33, load cells 2, 3) = 55mm

$$M_{LC} = F_1 \cdot 0{,}105 + 2 \cdot F_2 \cdot 0{,}525 \tag{12}$$

where,

F_1 – Force exerted by the farthest load cell (Figure 33, load cell 1)
F_2 – Force exerted by the nearest load cells (Figure 33, load cells 2, 3)

To achieve a static system is necessary that the moment from the load cells be equal to the moment of the tool.

$$M_{tool} = M_{LC} \tag{13}$$
$$1950 = F_1 \cdot 0{,}105 + 2 \cdot F_2 \cdot 0{,}0525$$

To solve this system of equations there is one more equation needed, that can be found by using the sum of vertical forces.

- Vertical forces (with moment)

$$\sum F_{ztool} = 0 \tag{14}$$
$$F_{ztool} - F_1 + 2 \cdot F_2 = 0$$

Solving the system formed by equation 13 and 14,

$$\begin{Bmatrix} 1950 = F_1 \cdot 0{,}105 + 2 \cdot F_2 \cdot 0{,}0525 \\ 13500 = F_1 - 2 \cdot F_2 \end{Bmatrix}$$
$$\begin{Bmatrix} F_1 = 16{,}6\ kN \\ F_2 = 1{,}55\ kN \end{Bmatrix}$$
$$F_1 = F_{zLC1} = 16{,}6\ kN$$
$$F_{zLC2} = \frac{F_2}{2} = 0{,}775\ kN$$

The maximum moments and forces measured by the load cells are summarized in Table 14. This table serves as a reference to determine the necessary capacity of the load cells.

Table 14 - Necessary capacity of the load cells.

Load cell capacity	Direction xx	Direction yy	Direction zz
Minimum value	2,2 kN	2,2 kN	16,6 kN

The chosen load cells were from the Michigan Scientific Corporation, model TR3D-A-5K, and their more important characteristics are summarized in Table 15[2].

Table 15 – Characteristics of the chosen load cell to SPI-A

Characteristics	Value	Image
Maximum load capacity	≈ 22241 N (5000lbs)	
Full Scale Output	4.0 mV/V, nominal, all channels	
Sensor	3 Four-arm strain gage bridges	

[2] The choice was also conditioned by the academic campaign on special prices for reconditioned load cells.

2.3.6 Structural Design

The structure of a machine must withstand the static and dynamic loads that result from the execution of its function. Its design and project should guarantee that the machine has the lowest deflection possible to ensure stability and accuracy during work.

The design of a machine mainly depends on the intended task. A combination of factors such as movements, capacity, effective area of work, assembly of modules, tool change, introduction of raw materials and maintenance should influence the design of the machine.

After a study and comparison with other machines of its kind the design chosen for SPIF-A structure was in arcade, because it allows a better distribution of compression and bending forces. Dynamic loads are not relevant for SPIFT process, which is relatively slow. The design of the structure is shown on Figure 34. The overall dimensions of the structure are 2700 mm of height and 1400 mm of width.

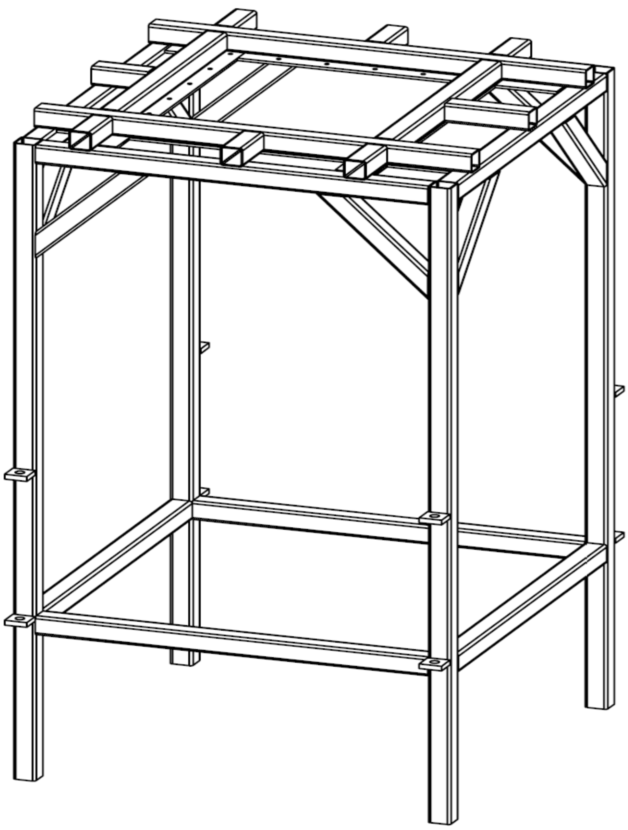


Figure 34 – SPIF-A structure.

The project of the structure should include the evaluation of the stresses imposed by static and dynamic loads.

- The static forces result from the existence of weight of the different components. They result in a static deflection and affect the accuracy between different parts of the machine.

- The dynamic stresses result from forces generated by movements of the machine as it operates. These vibrations and dynamic deflection may lead to loss of stability in operation.

Both static and dynamic forces are influenced by how the forces are distributed and absorbed by different parts of the structure. In SPIF-A's case, the effect of dynamic loads is negligible because the tools have low inertia and its operation is at low speeds.

To evaluate the effectiveness of the structure, an analysis was performed to the structure. This analysis took in account the maximum forces that the material to form will be submitted.

Figure 36 shows a diagram of forces applied to the metal sheet and subsequently transmitted to the structure. For the analysis, the forces were applied in two areas of contact. The first is the top of the structure that receives the forces through the Stewart platform (Figure 35, green zone), and the table where the metal sheet will be clamped (Figure 35, red zone).

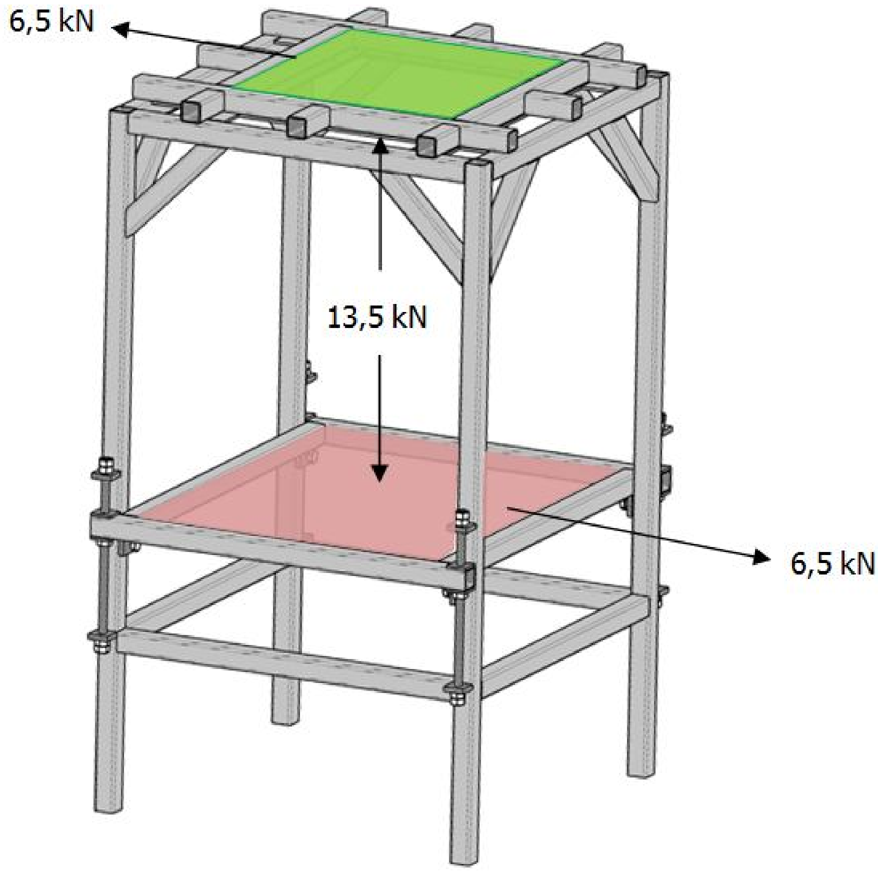


Figure 35 - Forces applied to structure, module and direction.

The obtained results from the software can be seen in Table 16.

Table 16 - Finite element analysis.

Software	$\delta_{max}\ (mm)$	$\sigma_{Von\ Mises}\ (MPa)$
Catia v5	0,286	28,2

The deformed view of the structure can be seen in Figure 36, with a factor scale of 100.

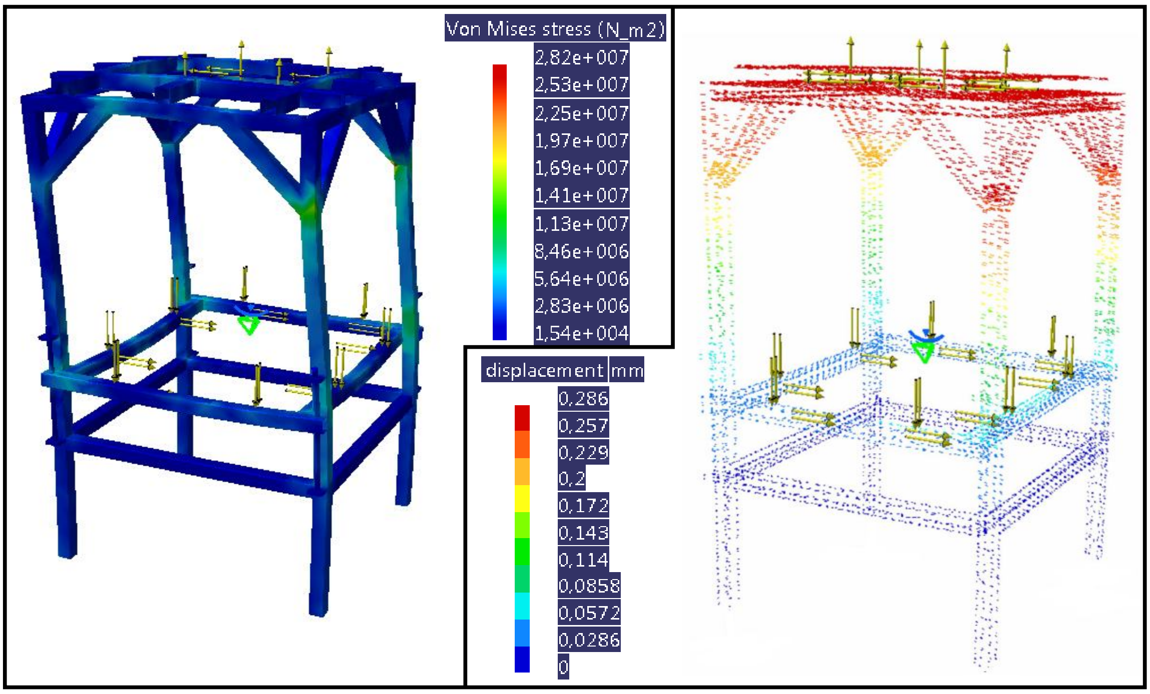


Figure 36 - Deformed aspect of the structure, Von Mises stress (left), displacement (right), CATIA V5.

2.3.6.1 Forming table

The design of the forming table was centered in obtaining an efficient fixation of the sheet while having the ability to adjust the size of working area, and the distance of the tip of the tool to the workpiece. That allows a maximization of the depth of the pieces to conform, and the ability to allocate the workpiece in un-centered positions. The vertical adjustment is made by using four threaded shafts.

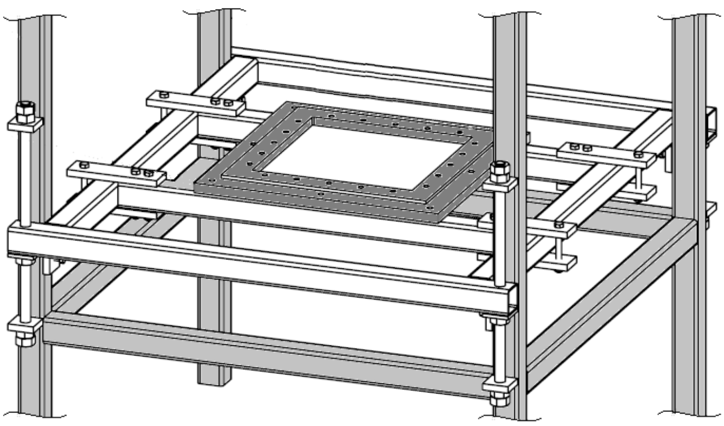


Figure 37 – Forming table.

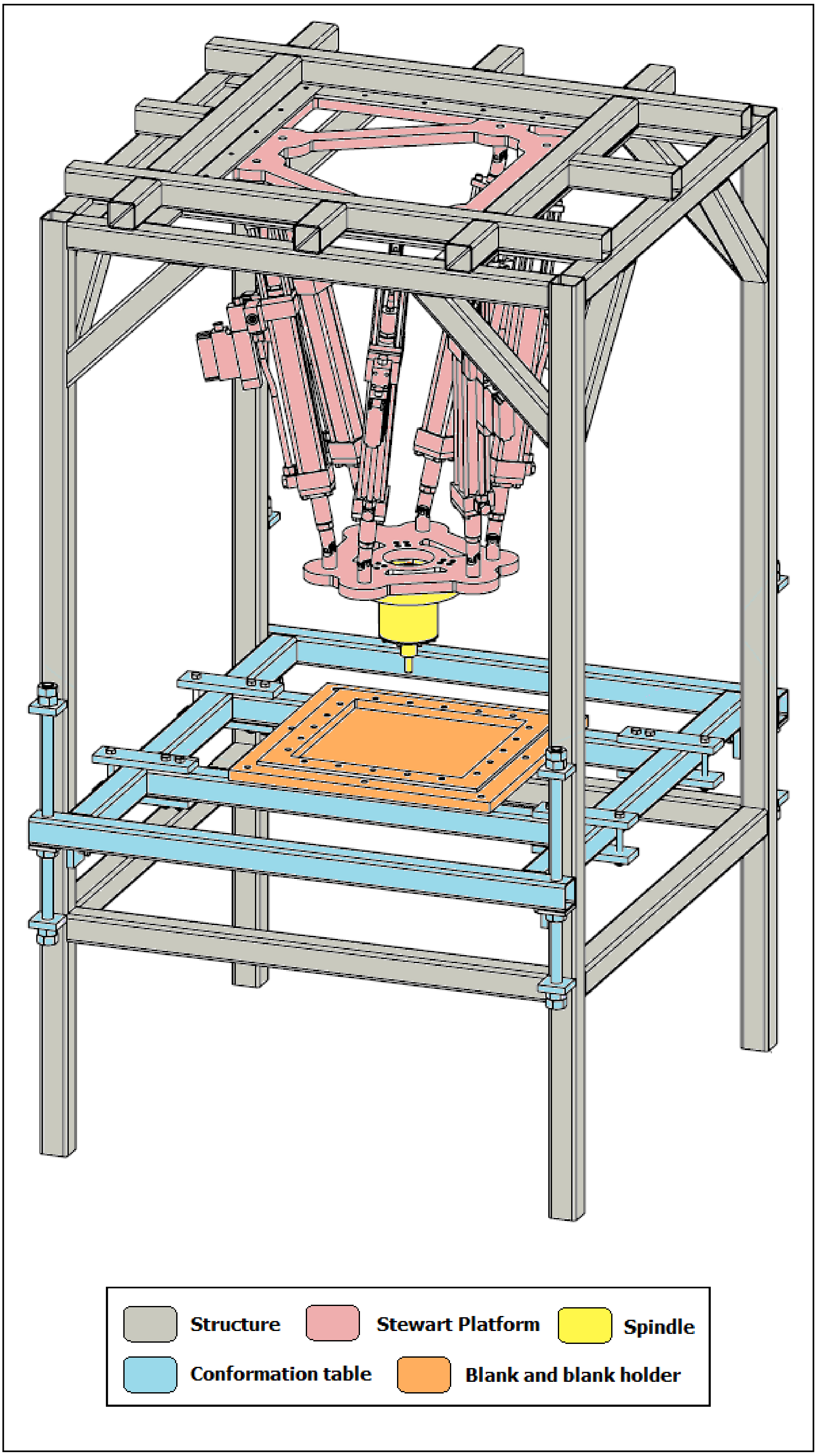


Figure 38 – SPIF-A assembly.

Chapter 3

3.1. Conclusions

This thesis had the objective of finalizing the project guidelines of a single point incremental forming machine named SPIF-A. From the analysis of the published work of various authors a conclusion can be made, that single point incremental forming is a recent technology, with a great field of applicability, but still needs to be developed. For that reason this project is more than necessary to contribute to the scientific community in developed this technology.

The stiffness and simultaneous flexibility of SPF-A will enlarge the field of application of incremental forming processes to harder materials and make possible the study of alternative tool paths.

In the end this project involved knowledge from various fields like structural design using a CAD tool and subsequently the simulation, hydraulic design, electrical design, and also commercial expertise, since the ultimate goal is to development a reliable machine while reducing the costs.

3.2. Future Work

Although the main project of SPIF-A is almost complete, there will be probably some amendments before its final version. The machine is currently under construction (Figure 39), which means that probably there will be slight differences between project and construction.

Since SPIF-A is a machine projected for incremental forming, a process that involves the calculation of toolpaths, an algorithm needs to be developed and in completion a control software must be also implemented in order to control the movements of the machine. Another area that needs to be addressed is the dimensional control of the state of forming. That can be achieved by the use of vision and image processing techniques. SPIF-A structure allows the inclusion of such technology, being the software for analyzing the data another issue. At last, a subject that doesn't directly involves this project, but can be use as a form of complementation and as a safety and efficiency measure is the development of simulation procedures.

Figure 39 – Construction of SPIF-A.

3.3. Bibliography

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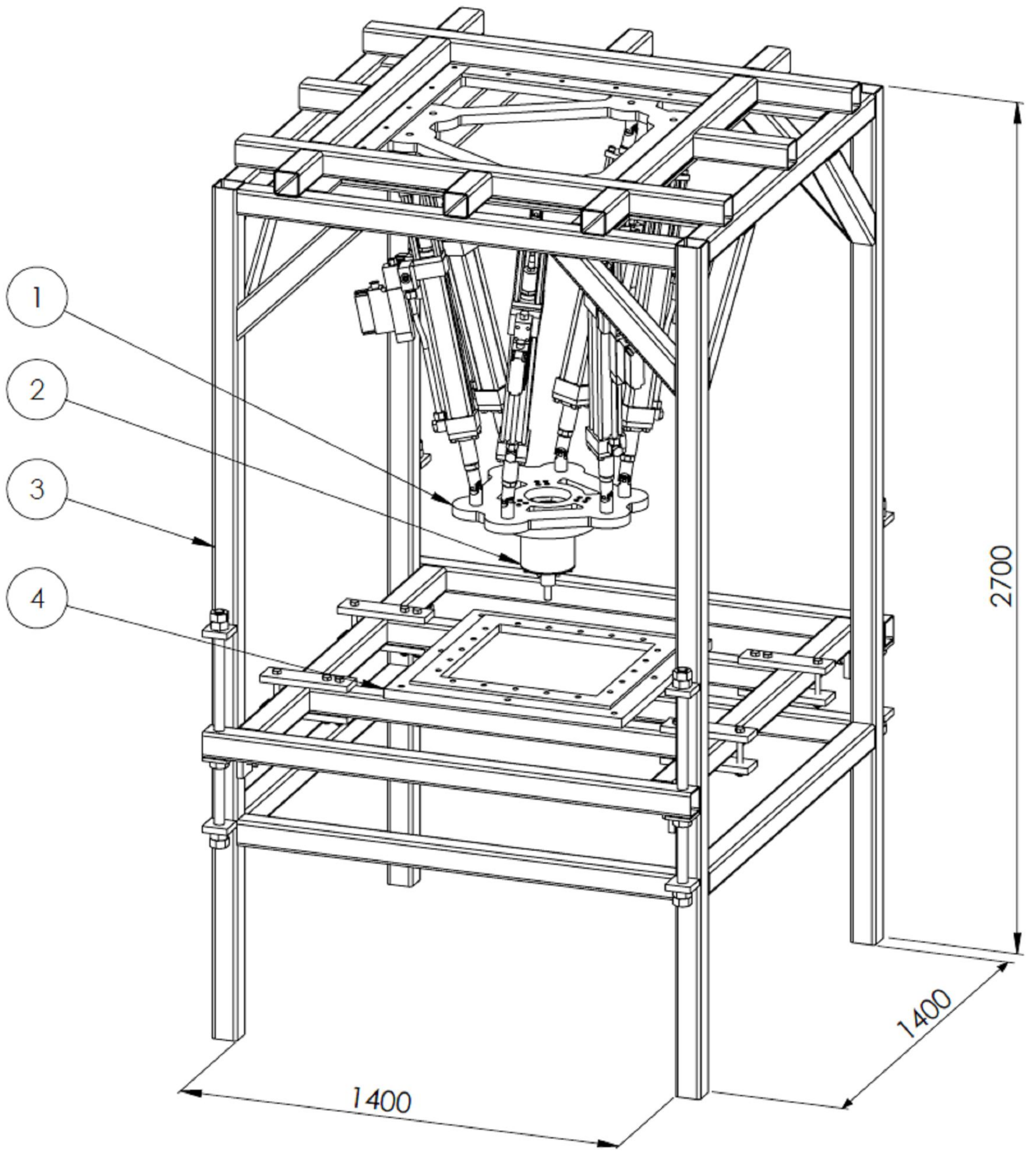
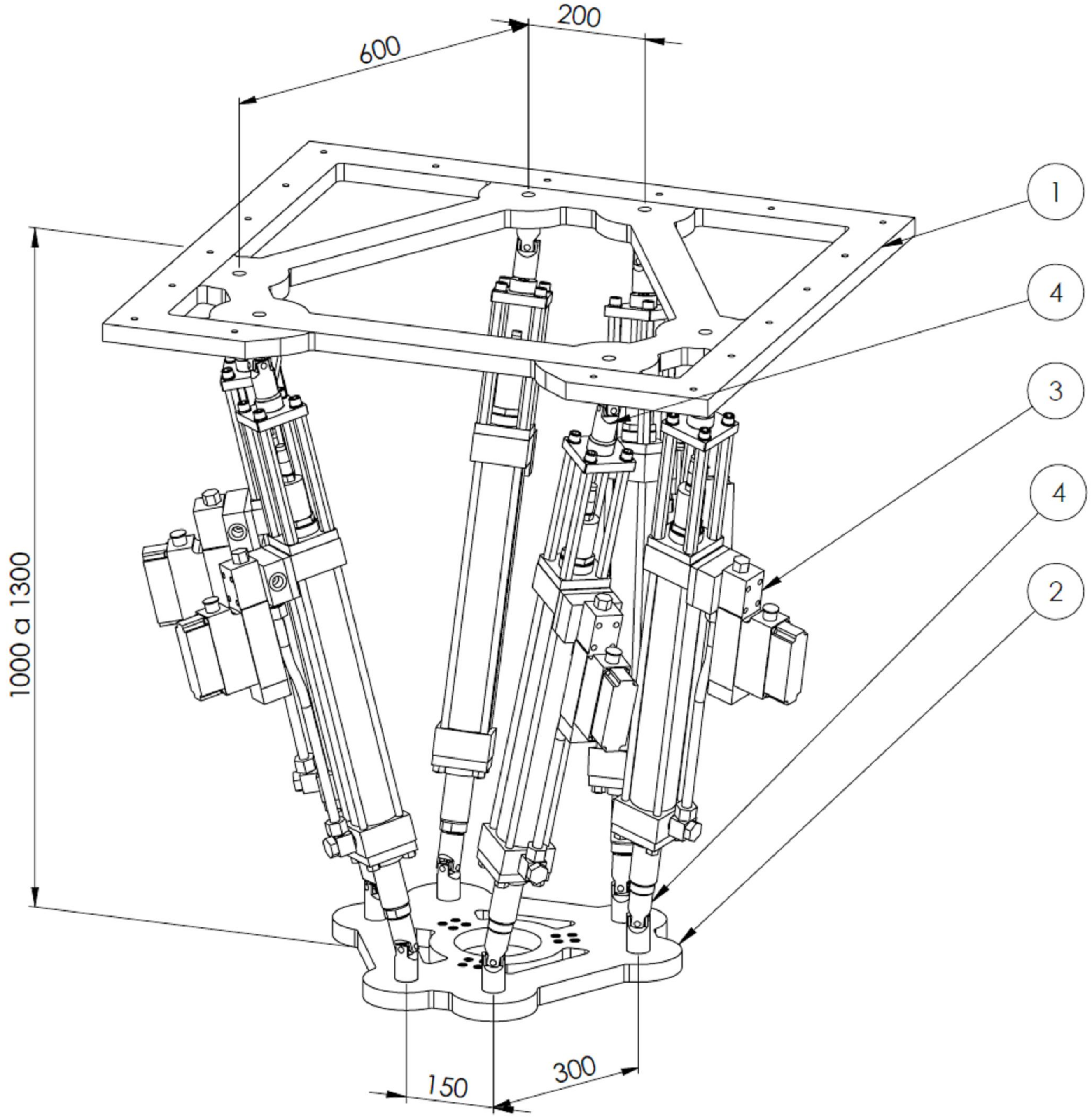
3.4. Appendix

Nº	Sistema	Descrição
1	Plataforma	Plataforma cinemática paralela com 6 d.o.f.
2		
3	Estrutura	Estrutura de suporte
4	Mesa	



DESIGNED BY: Miguel Martins Nº Mec. 36279	Departamento de Engenharia Mecânica
DATE: 21-03-2011	Universidade de Aveiro

Nº	Componente	Quant.	Fabricante	Referência
1	Plataforma base	1		
2	Plataforma móvel	1		
3	Cilindro hidraulico	6	Parker	
4	Cardan	12		
5	ISO 4762 M8 x 30 ---	12		



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DATE: 21-03-2011	Universidade de Aveiro

Nº	Componente	Quant.	Fabricante	Referência
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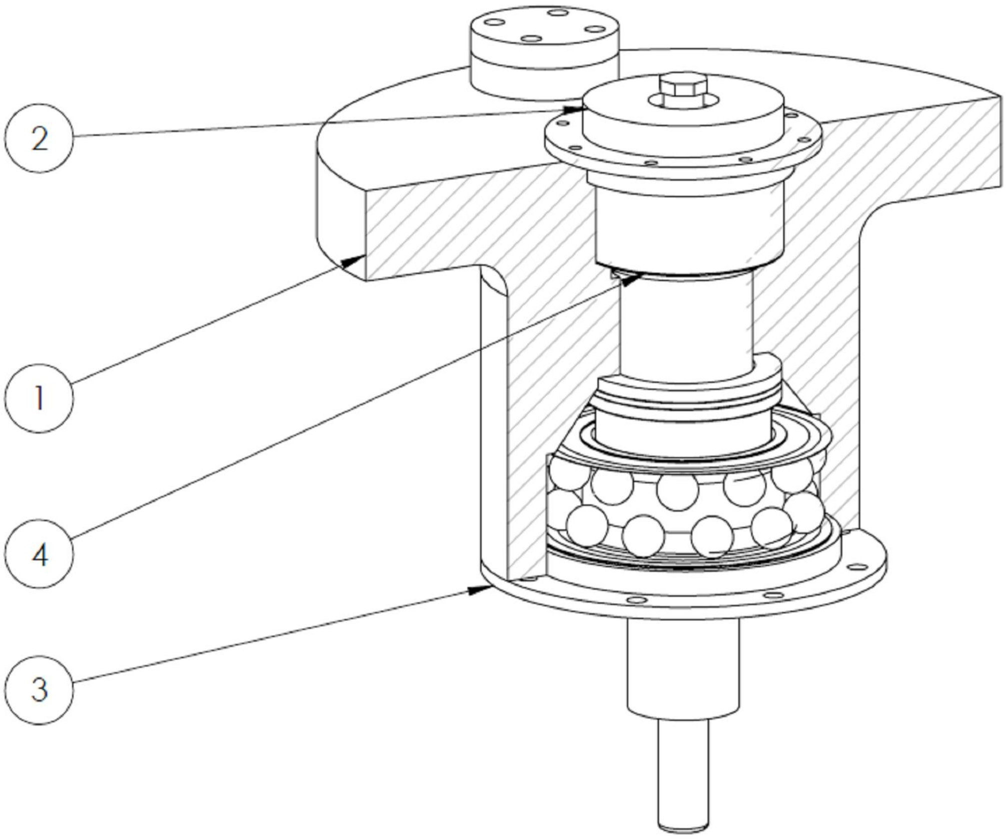
2	Tampa de cima	1		
3	Tampa de baixo	1		
4	Veio da árvore	1		



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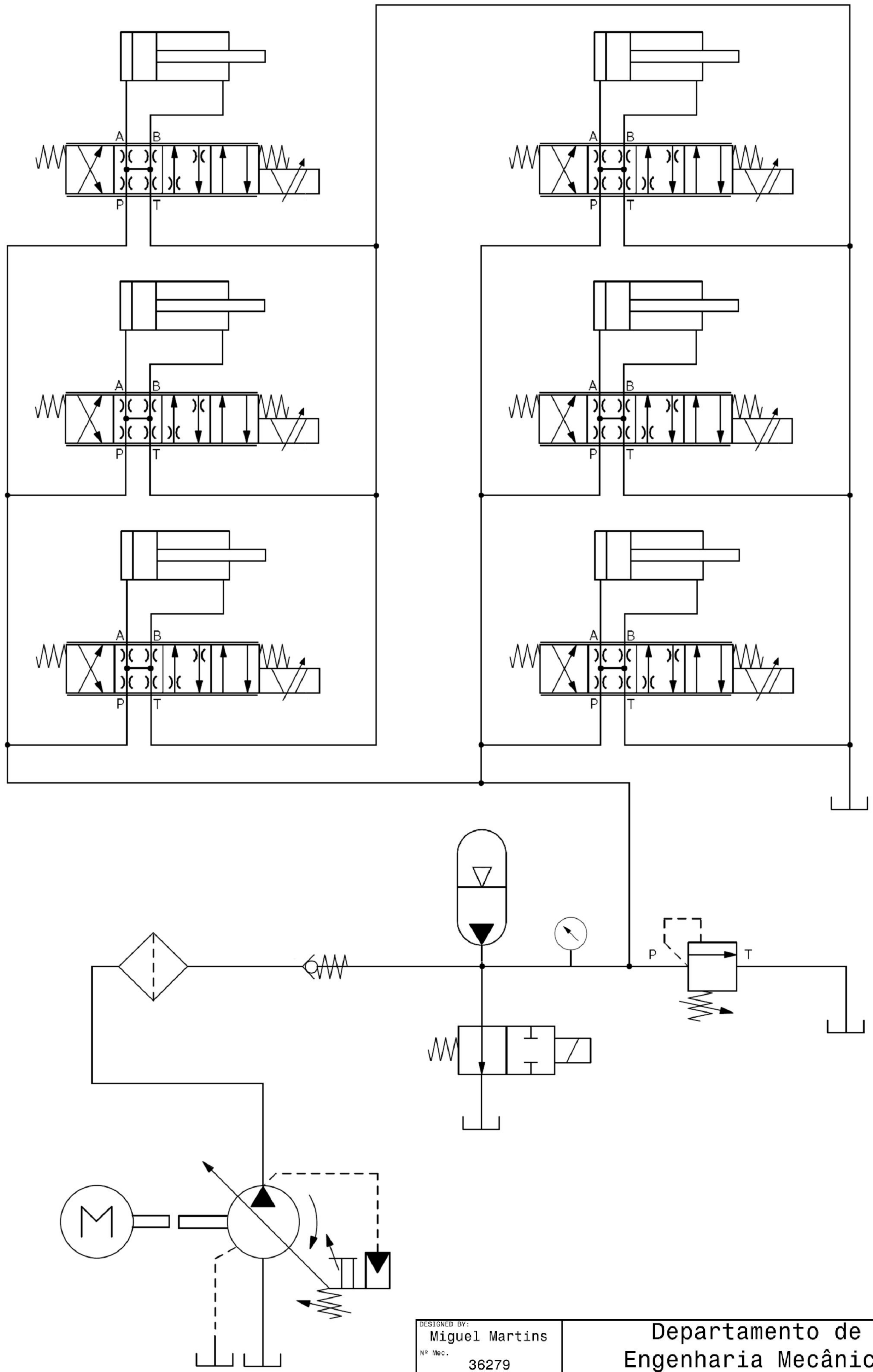

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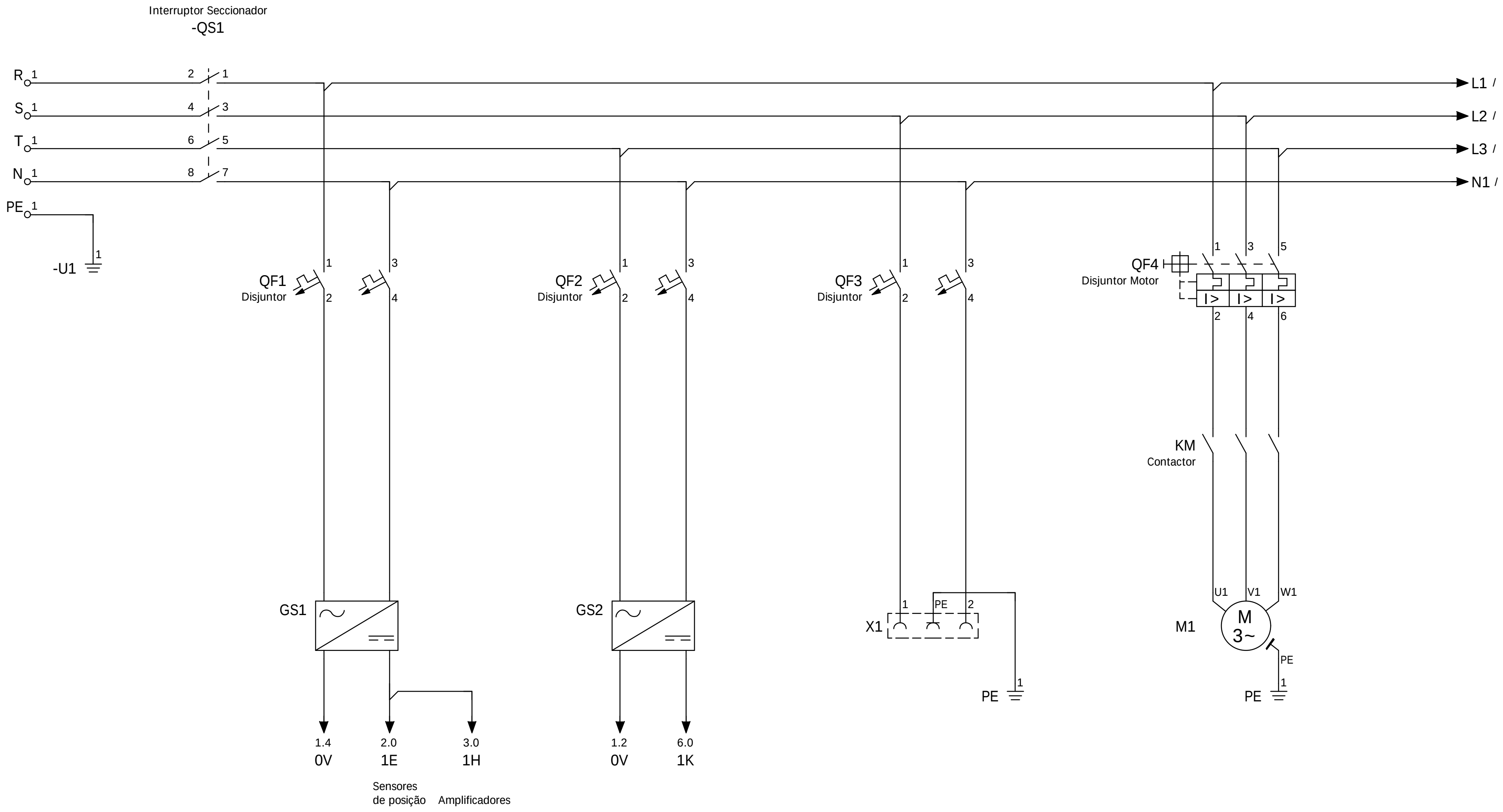

Alimentação Sensore e Amplificadores

Fonte de alimentação linear

Tensão 24V
Corrente 2A

Alimentação Electroválvulas

Fonte de alimentação comutada

Tensão 24 V
Corrente 21A

Tomada PC

Motor da Bomba Hidráulica

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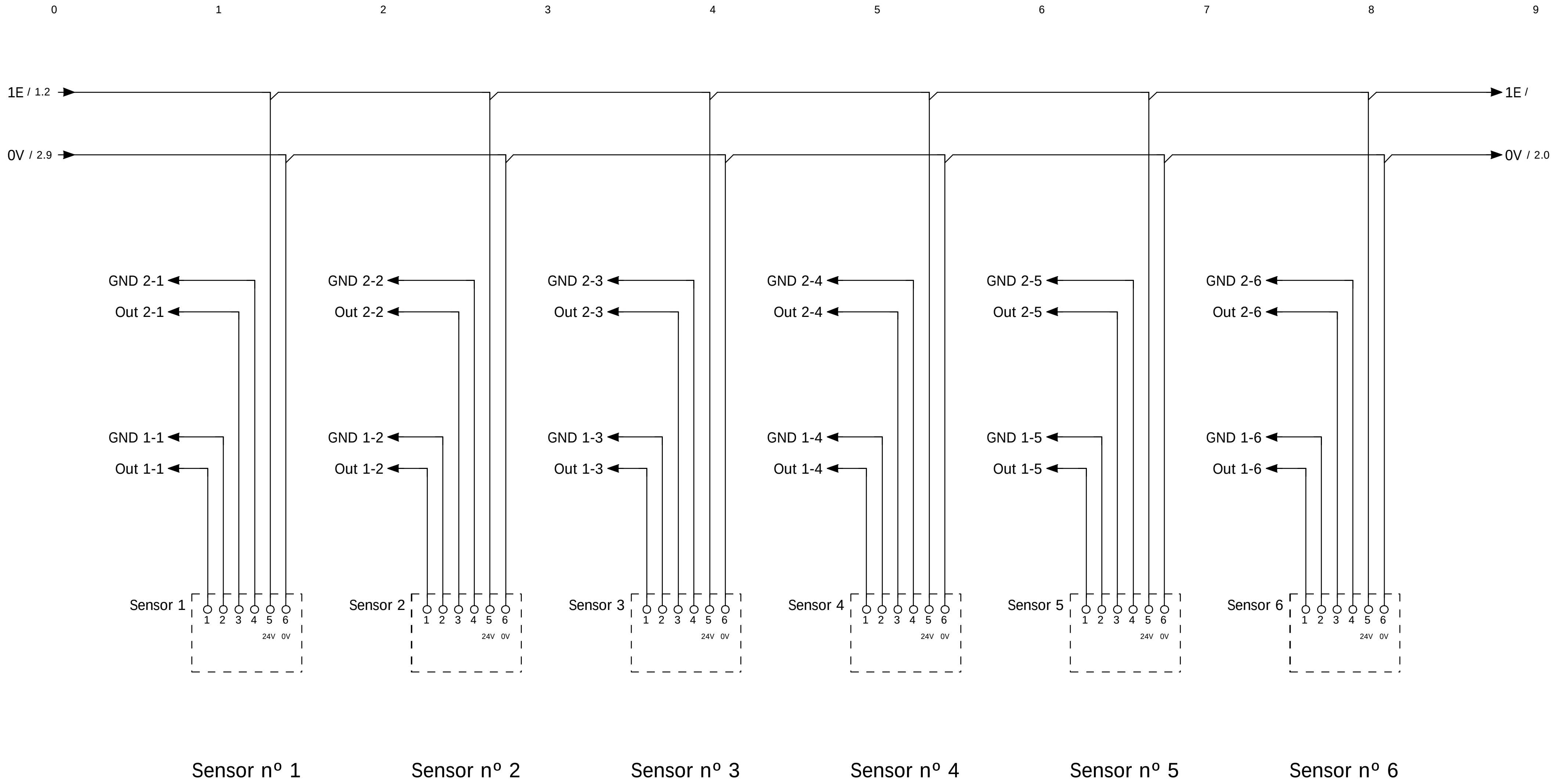

Próxima página
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Plano Electrico SPIF-A
Nº 1

SPIFA

Departamento de Engenharia Mecânica

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Sensores de Posição

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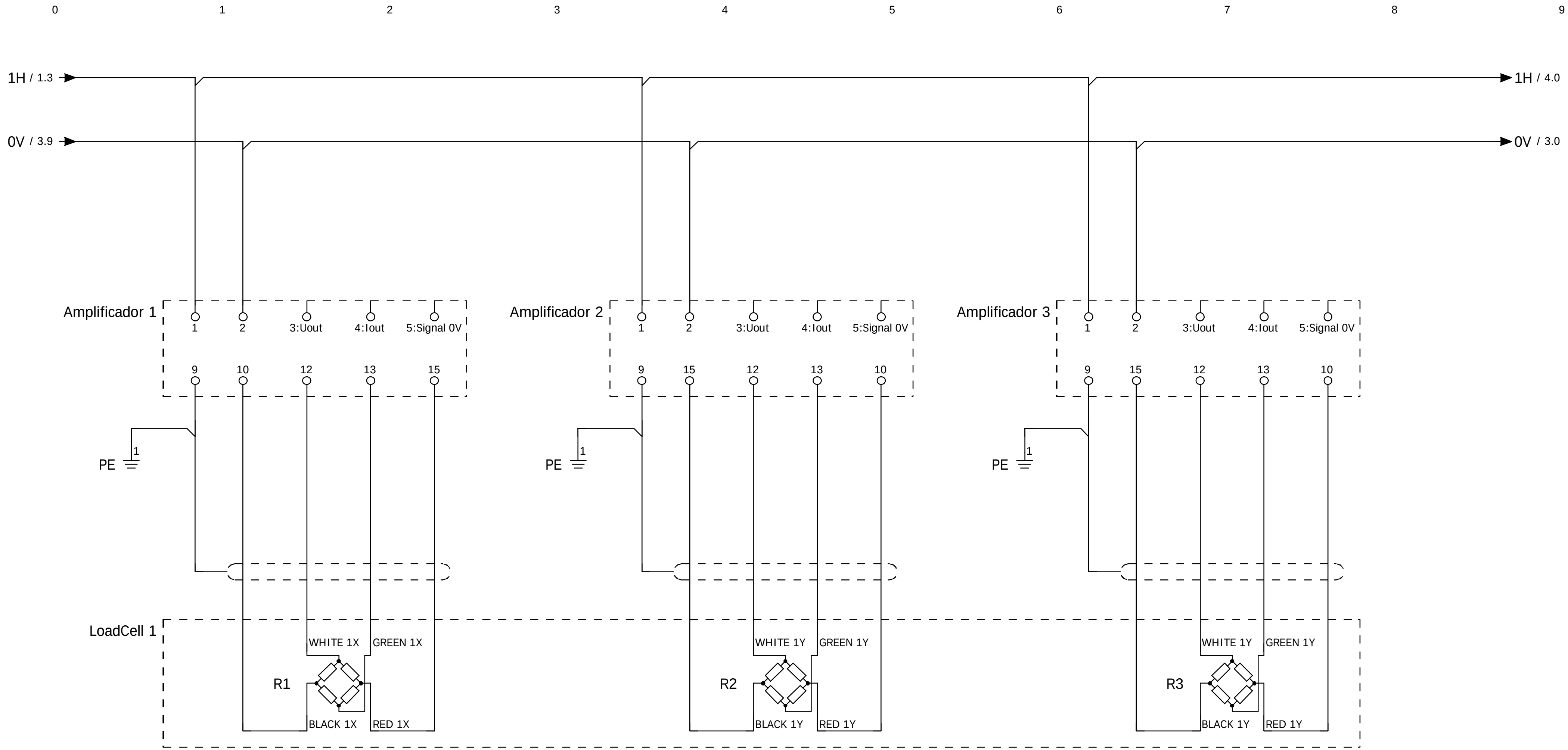

Ponte de Wheatstone para medição de deslocamentos em XX

Ponte de Wheatstone para medição de deslocamentos em YY

Ponte de Wheatstone para medição de deslocamentos em ZZ

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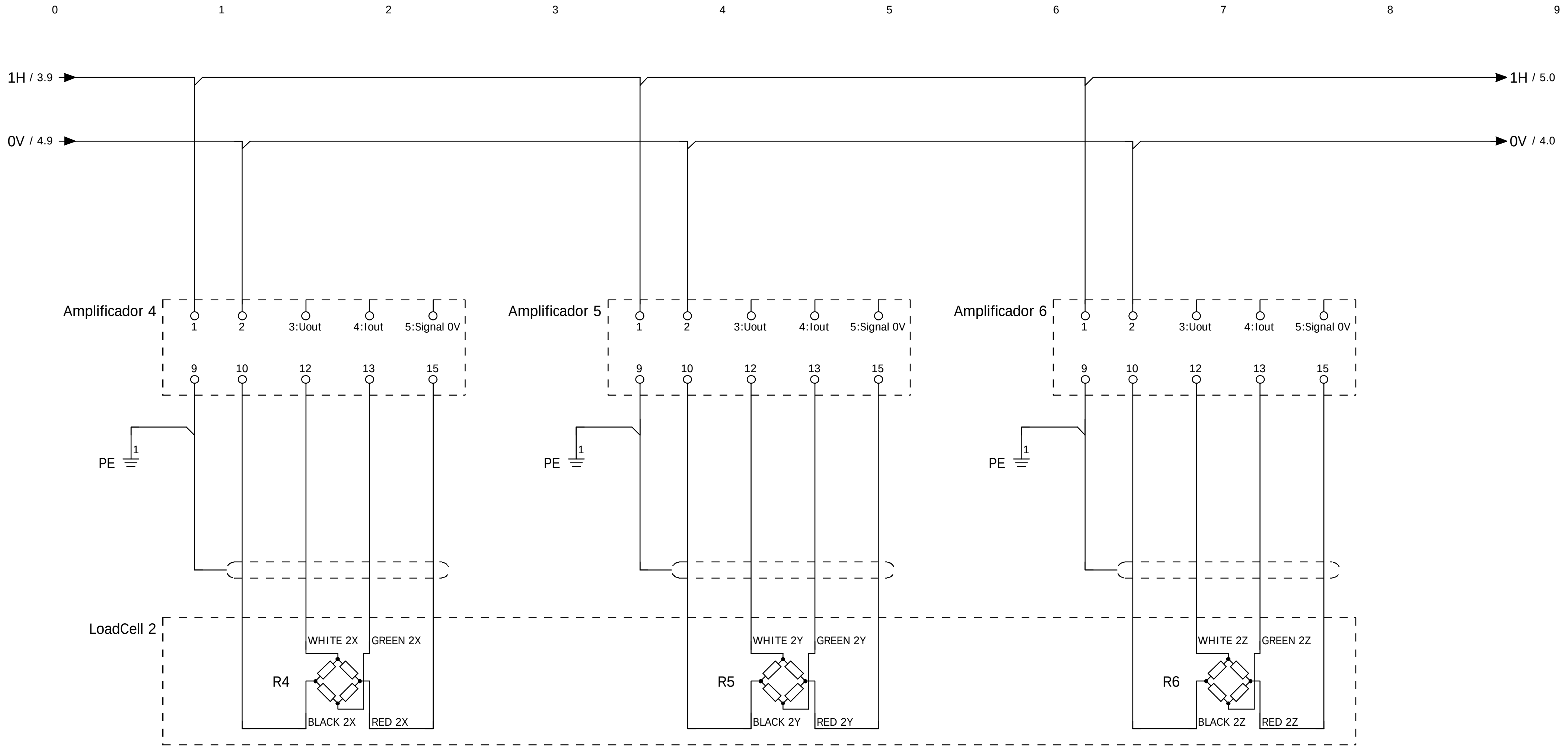

Ponte de Wheatstone para medição de deslocamentos em XX

Ponte de Wheatstone para medição de deslocamentos em YY

Ponte de Wheatstone para medição de deslocamentos em ZZ

Próxima página
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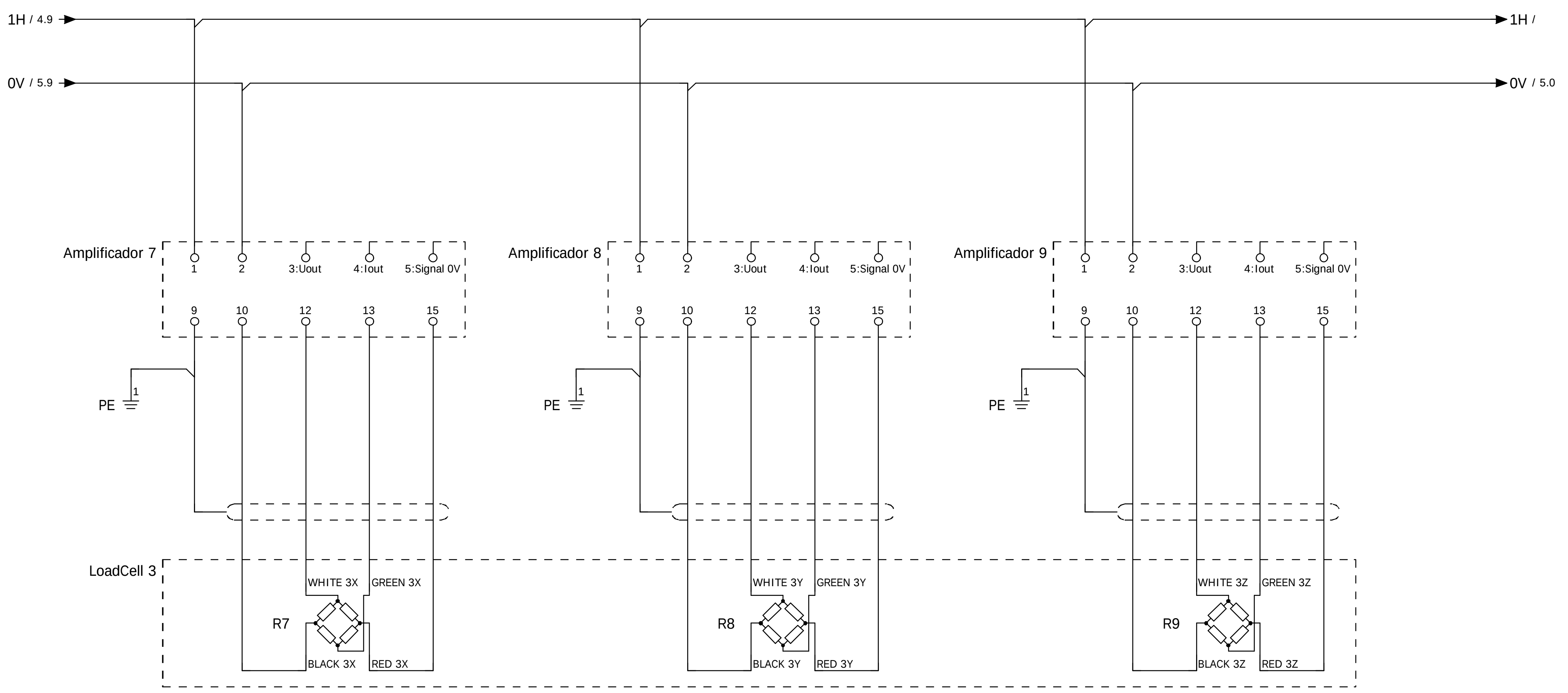
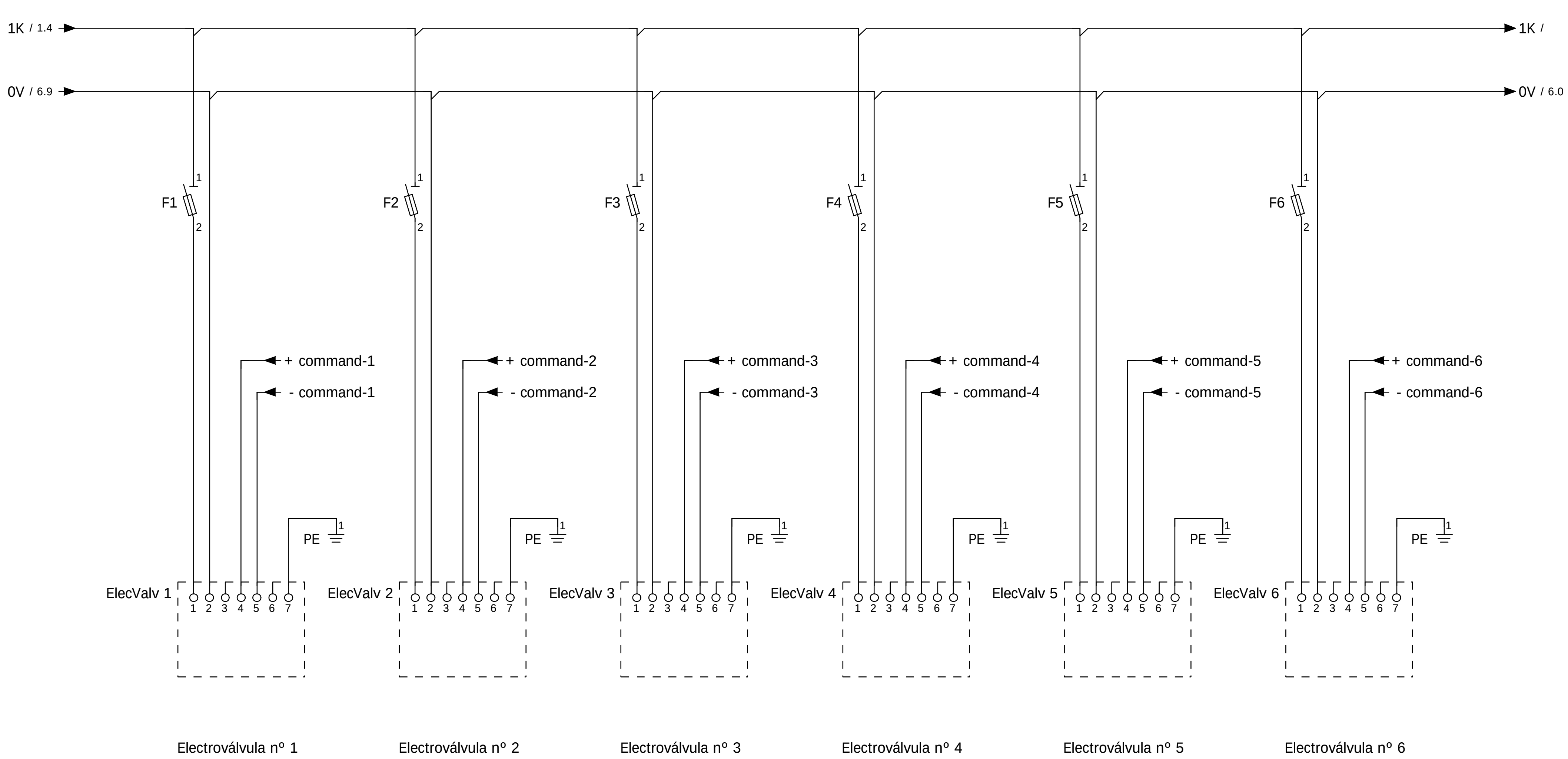


Ponte de Wheatstone para medição de deslocamentos em XX

Ponte de Wheatstone para medição de deslocamentos em YY

Ponte de Wheatstone para medição de deslocamentos em ZZ



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