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Development of a Three-station Creep Machine for Adhesive Joints Testing

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Resumo

Cada vez mais, os materiais adesivos demonstram a sua superioridade em relação a métodos de fixação convencionais. Ainda assim, só recentemente a indústria e o meio académico focaram os seus esforços na exploração destes materiais, pelo que é imperativo que se realizem estudos adicionais. O fenómeno de fluência em adesivos encontra-se especialmente mal estudado.

No Grupo de Adesivos da FEUP (ADFEUP), a investigação e caracterização de adesivos e juntas adesivas são os principais alvos de estudo. O grupo ADFEUP usufrui de vários equipamentos de teste, mas carece ainda de um equipamento especificamente dedicado a ensaios de fluência, que são, por natureza, extremamente morosos.

O principal objetivo deste trabalho é concluir a tarefa, iniciada em dissertações anteriores, de desenvolver e implementar uma máquina com capacidade para realizar simultaneamente múltiplos e independentes ensaios de fluência em juntas adesivas. A máquina deverá não só ser capaz de regular e manter uma determinada força nos provetes, mas também de medir e registar a força e os resultantes deslocamentos durante os ensaios.

Foi realizada uma revisão às propostas de *hardware* feitas nas dissertações de mestrado de Freire e Pina, seguida dos necessários ajustes e adições a cada um dos principais subsistemas: os componentes mecânicos, o circuito pneumático e o circuito elétrico. A máquina foi então montada e o *software* do sistema definido e implementado em *LabVIEW* com sucesso. Por fim, foram realizados testes que comprovaram as capacidades da máquina.

Abstract

Adhesives are increasingly proving their superiority over traditional joining methods. Notwithstanding, only in recent times have both the industry and the academia invested their efforts into the further exploration of these materials and so, additional studies are imperative. The phenomenon of creep in adhesives is particularly unexplored.

In FEUP's Adhesives Group (ADFEUP), the study and characterization of adhesives and adhesive bonds is the main focus of research. ADFEUP makes use of various testing equipments, but lacks a dedicated device capable of performing creep tests, which, by nature, are very time consuming.

This work's main goal was to conclude the task, already started in previous master dissertations, of developing and implementing a machine capable of carrying out multiple and independent creep tests on adhesive joints, simultaneously. The machine should be able to regulate and maintain a specific load on the specimens and to measure and record the loads and the specimens' resulting displacements during testing.

A revision of the hardware proposed by Freire and Pina's master dissertations, was carried out, followed by the necessary adjustments and additions to each of the three essential sub-systems: the mechanical components, the pneumatic, and the electric circuits. The machine was then assembled and the system's software defined and successfully implemented in LabVIEW. Lastly, tests were carried out, ascertaining the machine's capabilities.

Agradecimentos

Primeiramente e acima de tudo aos meus pais. Pelo apoio incondicional. Pela dedicação imensurável. Pela paciência inesgotável. Pelo amor inagualável.

Depois, com especial carinho, aos que comigo ingressaram: aos que, não vivendo comigo, foram partilhando casa, partilhando a vida. Aos que, entre a sua distração e desorganização, me foram guiando, caminhando passo a passo a meu lado. Aos que, entre mil e um projetos, conseguiram fabricar tempo para estar comigo, para cultivar a Amizade (e para rever este documento). Aos que me mostraram que dar absolutamente o máximo é o mínimo que posso fazer. Aos que me ensinaram a aplicar o conceito de integral à vida, tomando partido do mais ínfimo detalhe. Aos que, absolutamente fiéis aos seus valores, me mostraram o que é a verdadeira integridade. Aos teimosos casmurros, que me ensinaram o valor da persistência. Aos que, independentemente de quão chuvoso o dia, me presentearam continuamente com um sorriso na cara. Em suma, a estes que me enriqueceram todos os dias desta jornada e que me fizeram crescer muito mais do que alguma sala de aula seria capaz.

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A todos do grupo ADFEUP. Pela simpatia com que me acolheram. Pela disponibilidade que sempre me demonstraram. Por todo o acompanhamento durante este processo.

Ao Sr. Ramalho, ao Sr. Joaquim e ao Ângelo, sem os quais não teria sido possível passar do papel.

Por fim, aos meus orientadores professor António Mendes Lopes, professor Carlos Moreira da Silva e professor Lucas da Silva. Pela completa acessibilidade. Pela franqueza na crítica que me permitiu evoluir. Pelo contínuo acompanhamento. Por todos os ensinamentos.

Daniel Silva

“Most folks live and die without moving
anything more than the dirt it takes to bury them.
You get to change things.

...maybe even the world.”

Zachariah, "It’s a Terrible Life”

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Acronyms

ADFEUP	Adhesives Group of the Faculty of Engineering of the University of Porto
AI	Analog Input
AO	Analog Output
DADE	DADE Measured Value Converter
DAQ	Data Acquisition
DI	Digital Input
DO	Digital Output
FEUP	Faculty of Engineering of the University of Porto
GND	Ground
GUI	Graphical User Interface
I/O	Input and Output
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
PC IN	Computer Input
PC OUT	Computer Output
UTM	Universal Testing Machine
VI	Virtual Instrument
VPPX	VPPX Pressure Regulator Valves

Chapter 1

Introduction

1.1 Background and Motivation

Adhesives are arising as the best method for joining dissimilar materials, especially in fields were a lightweight approach is important.

Although we have been using them for quite some time, the production and development of adhesives is still a relatively new field and, because we have now realized of the many advantages in using adhesive joints comparing to traditional mechanical joints, the pertinence of further studies in this field keeps growing exponentially.

In FEUP, there is a group of researchers dedicated to explore the unknown aspects of adhesive bonding and confirm the (unproven) known properties and behaviours of these materials. FEUP's Adhesives Group (ADFEUP) makes use of varied testing equipment for the different research projects at hands. ADFEUP lacks however a machine capable of performing multiple, simoultaneous creep tests in adhesive joints.

Creep is one of the most general material behaviours. It can be characterized as a time dependant deformation that can lead to fracture [1]. Although this phenomenon has been intensely studied in metals, litle work has been published in the case of adhesives [2, 3].

To allow for new adhesives to be developed and for new applications of these materials in the industry, it is imperative that further studies are derived involving creep in adhesives. The experimental part of these studies is vital. However, because of the time dependency, creep tests can be extremely lengthy and that is why a multi-station dedicated machine for this kind of tests is a great asset for ADFEUP to have.

1.2 Objectives

The main goal of this dissertation is to continue the work of two FEUP's master dissertation students in developing a multi-station creep test machine for adhesive joints.

The specifications for the creep test machine had mostly been defined by these two students with the help of ADFEUP [4, 5].

The machine should be able to run tests at a constant load ranging from 200 N to 2500 N with a maximum displacement of 300 mm. It should have three stations where single lap joint or bulk specimens can be mounted upon, allowing for up to three simultaneous, independent, tests.

Although it is not an objective of this dissertation, a temperature chamber shall be able to regulate temperature conditions of the testing environment with temperatures ranging from $-100\,^{\circ}\mathrm{C}$ to $+200\,^{\circ}\mathrm{C}$.

The system shall enforce automatically the testing conditions and be able to acquire and plot the resultant displacement during the tests, saving the data along the way.

1.3 Methodology

The starting point of this dissertation was to assess the state of development of the machine.

Pina [5], supported on Freire's work [4], had completed the mechanical design of the machine and the main parts had already been manufactured. These were then assembled to detect any eventual design errors or missing parts.

After that, an assessment of the acquired components of the pneumatic and electric systems was made, followed by a thorough revision of the planed circuits and an analysis of the partially assembled electric circuit.

The circuits were altered, the missing components defined and ordered, while aiming to keep the associated costs to a minimum. They were then assembled according to the new circuits' plans and thoroughly tested.

Lastly, the commanding software was defined and programmed from scratch, the machine put into operation and some validation tests performed.

The machine, which at the starting point of the present dissertation, was in an unfinished state, the only major system close to completion being the mechanical parts, is now complete, apart from a minor electronic component, and able to perform creep tests.

1.4 Thesis Outline

Following the introduction, the second chapter presents a brief literature review on adhesives, on creep and on the available methods to perform creep tests. The third chapter focuses on the machine's hardware, being divided into three distinct sections: the mechanical design, the pneumatic circuit and the electric circuit. The implemented software and system behaviour are explored in the fourth chapter. In the fifth chapter several test results are presented and analysed and, finally, in the sixth chapter, the main conclusions are drawn and possible future developments addressed.

Chapter 2

Literature Review

This chapter consists of a brief literature review on adhesives, creep testing and the available methods to perform creep tests.

2.1 Adhesives

Adhesion is the term commonly used to describe the phenomenon where two dissimilar bodies are stuck together [6]. For millenia, mankind has been using naturally occurring adhesives and creating adhesive bonds using natural products and, since the twentieth century, began manufacturing its own adhesives, based on synthetic polymers [7].

The ability to join unalike materials, to bond thin sheets over large areas, to reduce the number of fasteners and holes in the structures - achieved, in general, with better stress distribution and increased stiffness over traditional mechanical joints - to increase fatigue resistance and vibration damping, and to obtain good cost efficiency and flexible joint design are often cited as advantages of adhesive bonds and the reasons why, nowadays, the industry is so interested in adhesive joints [8, 7].

Adhesives still present some downsides comparing to other technologies. Often is the case were the surfaces to be joined need special treatments and, because adhesives' shear strength and toughness are generally lower than in most metals, they are not so good when joining thick metallic components. On top of this, adhesive bonds are generally limited by their service temperature [2].

The employment of adhesives in areas such as the aerospace or the automotive industries, in which the safety of the materials is of paramount importance, demands a rigorous process control. Because non destructive testing methods cannot measure the joint strength directly and because there are still no universal methods to predict long term performance from short-therm tests, the study and characterization of these materials is a vital step in their further application in technologies and products [8].

2.2 Creep

Creep is an ongoing plastic deformation which, in time, can lead to the rupture of the material at hand [9]. In adhesives, the creep response is the result of the time-dependant untangling of the polymer chains [10].

In real applications, adhesive joints often have to endure sustained loading conditions, and, over time, all adhesives tend to deform, to creep. Unfortunately creep data rarely comes reported in the adhesive manufacturers' literature because creep tests are normally exceedingly long - what makes them also expensive [11].

A creep test is usually performed by noting the dimensional changes, i.e., measuring the deformation of the adhesive, when submitting the bonded specimen to a constant load, generally below the failing load required to break the bond, at a specific temperature, during a certain amount of time. Relaxation tests can also be performed where the ability of the adhesive to restore its former state on the removal of stress is studied [1].

A usual creep response exhibits three distinct phases, as shown in Figure 2.1:

Primary creep The deformation is transient and the speed of deformation decreases regularly. At this stage the creep resistance increases due to the deformation itself.

Secondary creep The speed of deformation is time independent and minimal. This stage is the result of a balance between the hardening and restoration phenomena.

Tertiary creep The deformation speed rises until the rupture of the material [9].

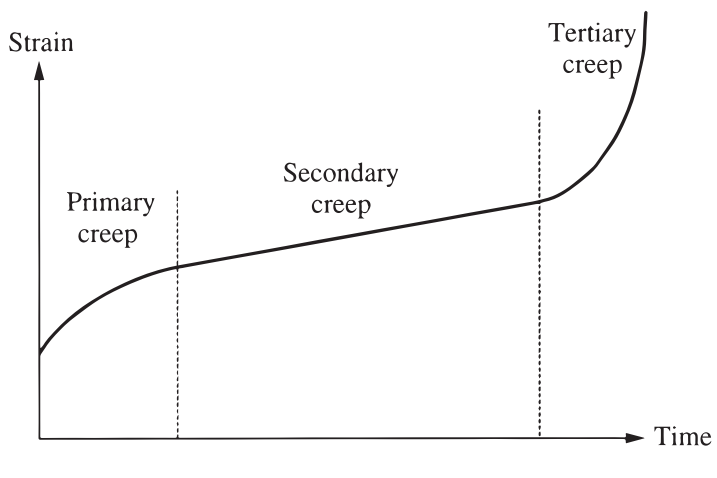


Figure 2.1: The three stages of creep behavior [10].

The temperature plays a big part in creep response and, in general, higher temperatures mean substantially higher creep rates (Figure 2.2). In thermosetting polymers, the creep response is often negligible below the glass transition temperature. However, in contrast to metals, a greater recovery of the strain can be achieved upon the removal of the load [10, 12].

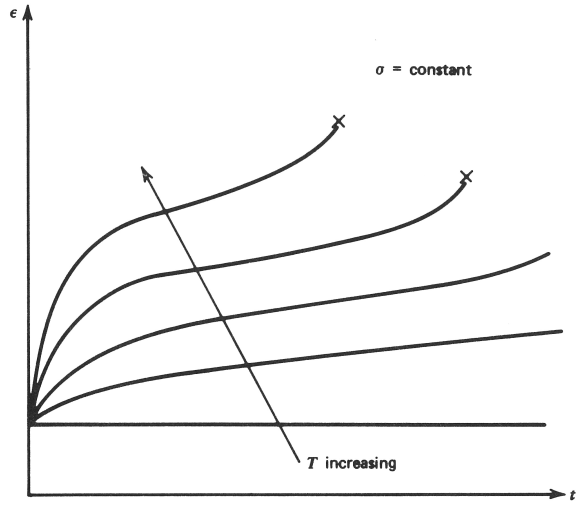


Figure 2.2: Effect of temperature on the creep curve at constant stress [1].

2.2.1 Creep Test Specimens

Creep tests can be performed using various types of specimens, with diverse geometries. Two of the most commonly used kinds of specimens for these tests are the bulk specimen (Figure 2.3) and the single lap joint (Figure 2.4).

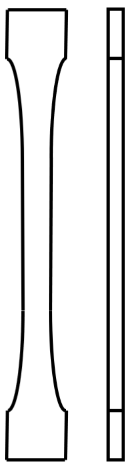


Figure 2.3: Bulk Specimen

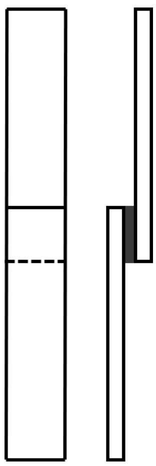


Figure 2.4: Single Lap Joint Specimen

Bulk specimens are usually produced by pouring or injecting the adhesive into a mould or, if the viscosity of the adhesive allows it, under pressure, between plates. Tests with these kind of specimens follow the standards used for plastic materials and are normally easy to perform [13].

Because in the real-world applications of adhesives, these are largely used with very small thicknesses, tests using thin sheets of adherends, especially using single lap joint specimens are very common as this kind of specimen reproduces closely joints used in many structures, especially in the aeronautical industry [13].

2.3 Commercial Creep Testing Mechines

There aren't many manufacturers offering multi-station, creep dedicated testing solutions. The solution often suggested for creep testing is to use universal testing machines (UTM). These can usually perform tensile, compression and bend tests and, as creep tests are, in its essence, tensile tests, the machines can also be used for creep testing. As they are not usually specific for adhesive testing, the machines' load capabilities are often much higher than the required to perform creep tests on adhesives.

Manufacturers like MTS, Labthink, Marx Test, Shimadzu, United Testing, and Testometric offer several UTM options, with climatic chambers also available to allow tests at different temperatures. The last two manufacturers even commercialize multi station UTMs. Despite this, as is the case of the great majority of commercial multi-station machines, Testometric and United Testing's multi-station UTMs (Figures 2.5 and 2.6, respectively) only allow simultaneous testing, at the same load.

Figure 2.5: Testometric's multi-station UTM [14].

Figure 2.6: United Testing's multi-station UTM [15].

Zw*i*ck offers a multi-station electromechanical creep testing machine (Figure 2.7). The machine has 5 individually controlled test axes, each with a maximum load capacity of 10 kN. It can perform creep and relaxation tests and has been designed specifically for long term tests, being able to perform experiments lasting up to 10 000 h. A temperature chamber can also be acquired from the manufacturer, allowing tests between −70 °C and +250 °C [16].

Figure 2.7: Zw*i*ck's multi-station creep testing machine [16].

INSTRON also offers a multi-station solution capable of performing up to 5 simultaneous, independent tests (Figure 2.8). Each station's load capacity is the total system load capacity (30 kN) divided by the number of load stations being used. Nonetheless, only the center load station can accommodate full capacity; all other stations are rated to a maximum of 10 kN. INSTRON also commercializes an environmental chamber, accommodating test temperatures from −40 °C to +200 °C.

Figure 2.8: Instron's multi-station UTM [17].

2.4 Creep Testing Solutions in FEUP

ADFEUP has an INSTRON 3367 dual column tabletop testing machine (Figure 2.9) with an INSTRON 3119 environmental chamber. This UTM can perform tests up to a maximum force of 30 kN. The environmental chamber allows for temperature control between $-100\,^{\circ}$C and $+350\,^{\circ}$C [18, 19].

Notwithstanding the machine's ability to perform creep tests, ADFEUP uses it daily for its several other projects and cannot afford to have the machine performing lengthy creep tests, sacrificing precious testing time.

ADFEUP also owns a set of testing apparatus that use springs to apply tension to the specimens (Figure 2.10). The problem with these derives from Hooke's Law: as the specimen is deformed, the spring's length changes and so does the exerted force. Besides this, a mechanical indicator (Figure 2.11) is used to monitor the changes in the specimens' length which requires manual readings and registry.

Because of the presented drawbacks, ADFEUP usually resorts to a simpler method when performing creep tests: to use weights attached to the specimen as the load application mean (Figure 2.12). The manual readings and registry are still required, but, as gravity doesn't change, the exerted force on the specimens is constant.

Figure 2.9: An INSTRON 3300 series testing machine [18].

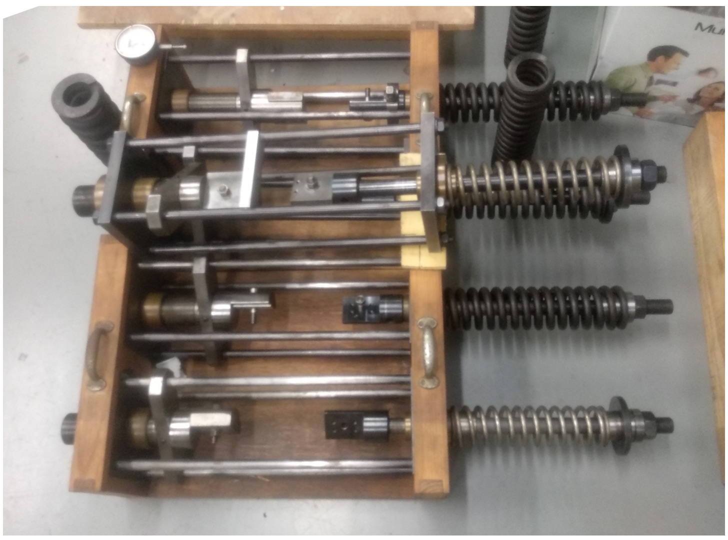


Figure 2.10: ADFEUP's spring testing apparatuses.

Figure 2.11: A mechanical indicator used to monitor changes in the specimens' lenght.

Figure 2.12: Creep test using weights.

2.5 Discussion

Adhesive joints provide significant advantages over traditional joining methods and are increasingly drawing attention from the industry. Because of this, further study of this materials is required, especially regarding the creep phenomena.

As the defining characteristic of creep is time dependency, creep tests are usually lengthy. Besides this, the commercial offer of machines dedicated to this kind of testing is very limited: most multi-station test machines allow for independent tests but only under the same loading conditions, there are no multi stations machines dedicated to adhesive joints testing and the machines available are exceedingly costly. Because of this, manual testing is often the option taken to spare expensive testing machines for other kinds of research.

For these reasons, a multi-station machine dedicated to creep testing would be a valuable asset to ADFEUP: not only would it spare the labour associated with manual testing but also allow more precise results and confident data, without any interference with other running projects. By developing and manufacturing this machine in FEUP, not only can we tailor it specifically to ADFEUP's needs but we are also able to save significant amounts of money compared to the costs of acquiring a commercial machine with similar capabilities.

Chapter 3

Hardware

This chapter addresses the machine hardware. The solutions proposed in previous dissertations are analysed and the implemented alterations are explored. The chapter is split into three sections: Mechanical Design, Pneumatic Circuit and Electric Circuit. Each, in turn, addressing two topics: the proposed and the revised hardware.

3.1 Mechanical Design

Pina [5] revised the work of Freire [4] on the machine design, carrying out significant changes and improvements.

Pina's machine (Figure 3.1) consisted of 6 **mechanical wedge action grips** (1), assembled in pairs, forming 3 testing stations.

The **upper assembly** (2), contains the 3 upper grips, the 3 load cells, the upper couplings between each of these sets, each ending in an axial spherical plain bearing, and all the necessary connections between these elements.

The **lower assembly** (3), contains the 3 pneumatic cylinders and their connections to the lower grips and to the lower beam. Both Freire and Pina planned for a future installation of a Climatic Chamber, encapsulating the testing zone and so, precautions were taken into account to negate its possible undesired effects on the functioning of the machine, namely assuring that the pneumatic cylinders were adequately spaced from extreme temperature sources and that all the materials would resist a broad temperature spectrum (which by ADFEUP specifications will range from $-100\,°C$ to $+200\,°C$).

The **machine structure** (4) consists of a test frame formed by an upper beam and a lower beam, connected by two columns. This frame is assembled on top of a support frame which sustains the entire machine.

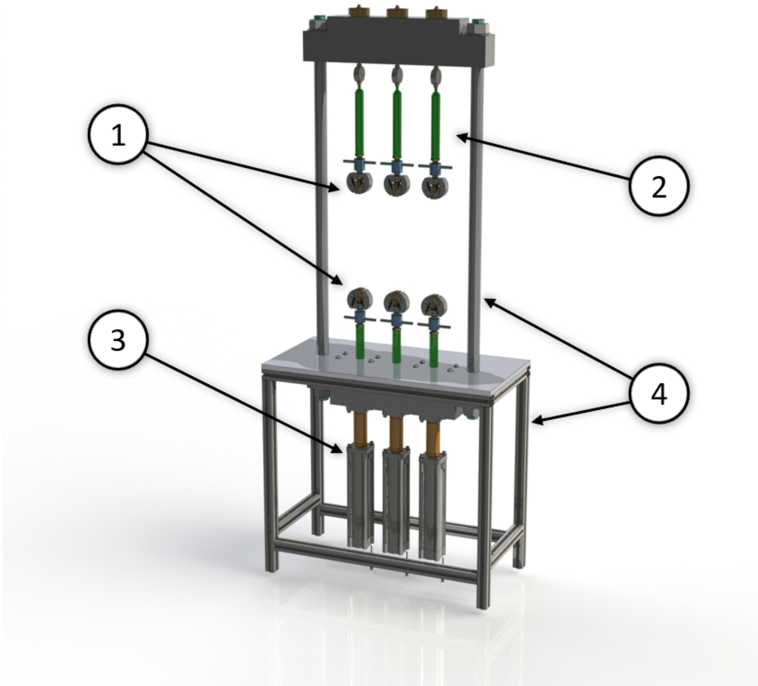


Figure 3.1: Pina's creep test machine mechanical design [5].

With the exception of some connecting parts, such as missing screws and bolts, most mechanical components of the machine were already manufactured as per Pina's design. All except the heat sink, which becomes only relevant when the climatic chamber is implemented - which falls out of this dissertation's objectives - and the extension springs, which pull the jaw faces of the grips against the shoe (Figure 3.2), allowing for the proper placement and tightening of the specimens. The springs are designed as described in the follow-up.

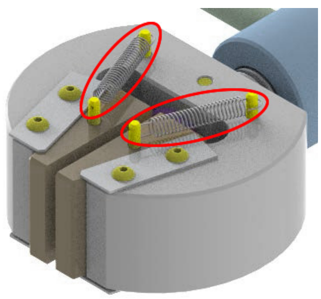


Figure 3.2: Grips' jaw faces extension springs [5].

At their rest position, the springs have to ensure that the jaw wedges are as far apart as possible, allowing for maximum grip opening in that state. For this reason each set of two springs has, in the aforementioned state, to counteract the weight of a jaw face wedge. Each wedge has a mass under 250 g, which results in an approximate weight of $9.81 \times 250 = 2.45\,\text{N}$.

The centres of the screws holding the springs in place are 42.3 mm apart when the grip is at its maximum opening, and 49.3 mm when it is fully closed without any specimen between the jaw faces. These screws are ISO 4762 M4×12 screws, meaning that their 4 mm diameter has to be taken into account when choosing the springs, as the following scheme shows (Figure 3.3):

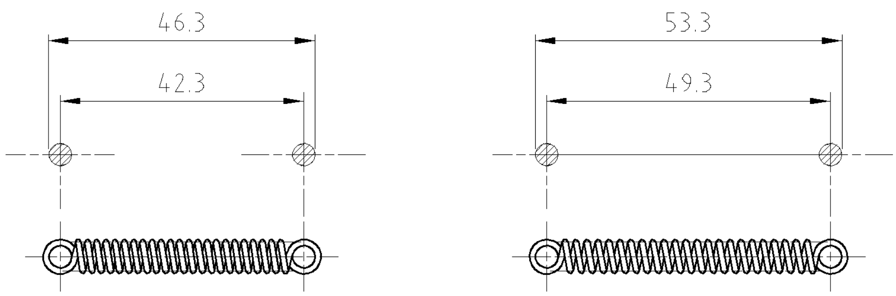


Figure 3.3: Grips' jaw faces springs minimum (left) and maximum (right) extension.

An extension spring stiffness, k, can be calculated by

$$k = \frac{1}{8}\frac{d^4 G}{n {D_m}^3} \tag{3.1}$$

where d is the nominal diameter of the spring wire (mm), G denotes the shear modulus of elasticity (N/mm^2), n is the number of active windings and D_m represents the coil mean diameter (mm) [20].

The company Fanamol, uses Inox AISI 302 steel, which has a shear modulus of 70.3 kN/mm^2, to manufacture springs. Iterative calculations with the available springs led to a spring with the following characteristics: $n = 28$, $D_m = 7\,\text{mm}$, $d = 1\,\text{mm}$, $L_0 = 44\,\text{mm}$. The parameter L_0 being the undeformed length of the part.

Considering a linear spring behaviour, according to Hooke's Law, the force, F, required to extend (or compress) a spring is directly proportional to its extension, δ:

$$F = -k\delta \tag{3.2}$$

being k, the spring's stiffness, a constant factor.

Through Equations 3.1 and 3.2, a minimum force of 2.1 N, when the spring is at its rest position, and a maximum force of 8.5 N, when the jaws are fully closed, can be determined. These values, the lower one being almost two times the required minimum force, make allowance for some eventual loss of spring elasticity due to the effects of time and repetitive use.

Upon machine assembly, a severe design overlook was discovered. With the cylinders fully extended, there is a gap of roughly 170 mm between each set of upper and lower grips. ADFEUP's specimens usually do not exceed 70 mm, most of them being considerably shorter. To mend this problem an extension to the upper coupling was designed. Ease of fabrication and integration with the already produced components was prioritized.

The extension rod devised (Appendix A.1) is a simple $\phi 40 \times 200$ cylinder with threaded ends projected to assemble, without the need of additional parts, between the upper coupling and the load cells. It is manufactured in the same steel as the upper coupling (AISI 304 austenitic stainless steel) to negate the effects of temperature variations due to the climatic chamber operation.

3.2 Pneumatic Circuit

Pina [5] proposed a pneumatic circuit including an air treatment unit feeding three pressure lines, each with a proportional pressure regulator valve, a directional valve, a cylinder, two flow control valves and two proximity sensors.

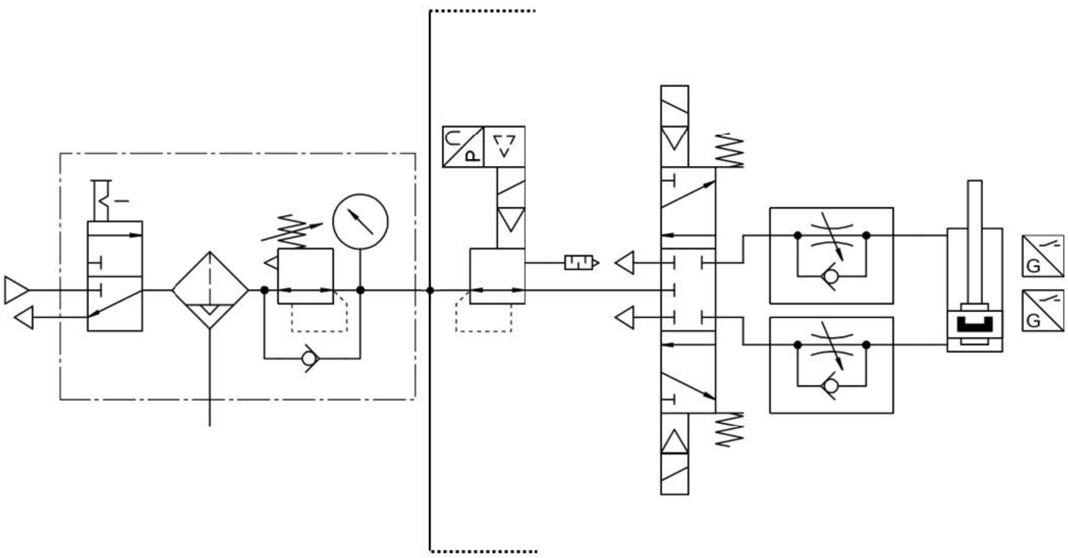


Figure 3.4: Pina's pneumatic circuit proposed scheme [5].

The sugested pneumatic circuit scheme (Figure 3.4) shows only one of the stations as the remaining two are identical, after the air treatment unit. The suggested pneumatic circuit was adopted with a minor alteration (discussed in more detail in subsection 3.2.7) and some specific components replacement.

At the starting point of this dissertation the proportional pressure regulator valves and the cylinders had already been acquired by ADFEUP, as selected by Pina.

3.2.1 Cylinders

The chosen means to convert the power available in FEUP's compressed air network in the form of pressure into the forces needed to perform creep tests were three Festo DDPC-Q-80-300-QA cylinders (Figure 3.5). These are standard cylinders with an integrated displacement encoder. They have a stroke of 300 mm and a $\phi 80$ diameter piston with protection against rotation. Their working temperature can range from −20 °C to 80 °C. At 6 bar the cylinders can exert a theoretical advancing force of 3016 N and a theoretical retracting force of 2721 N. The cylinders are prepared for positioning sensing via external proximity sensors.

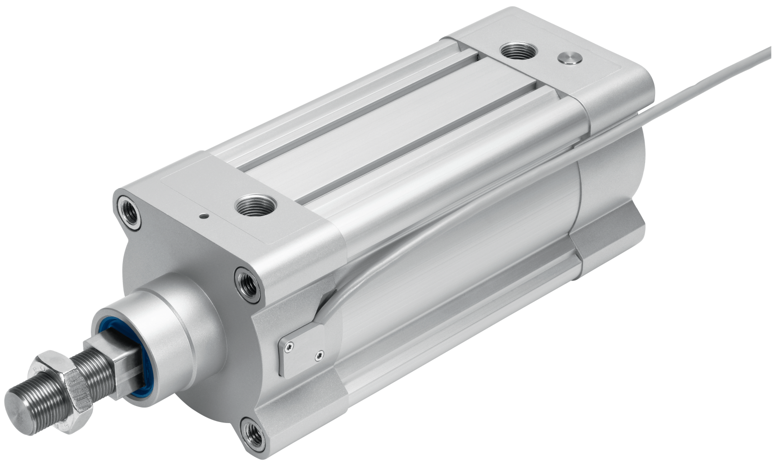


Figure 3.5: Pneumatic cylinders [21].

3.2.2 Pressure Regulator Valves

To control the pressure in the cylinders' active chamber, and therefore the load applied on the specimen, one has to regulate it. This is achieved through the use of Festo's VPPX-8L-L-1-G14-0L10H-S1 valves (Figure 3.6), from now on referred to as VPPX.

Figure 3.6: VPPX [22].

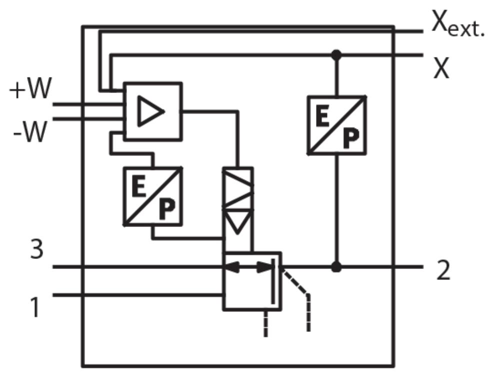


Figure 3.7: VPPX schematic [22].

In Figure 3.7 a shematic of the VPPX valves is presented. The references in the next paragraph regard this image.

The VPPX valves have three connections to the pneumatic circuit: a supply port (1), a pressure output (2) and an exhaust port (3). The valves are designed to control pressure from 0.1 bar to 10 bar, having two operating modes: in the internal mode the valve uses an integrated pressure sensor at the pressure output and compares its signal (X) to the setpoint value (W), regulating the output flow to minimize the difference between these two; in the external mode the valve compares instead an external value (X_{ext}) to the setpoint value (W).

We wanted to use the external control mode, feeding the valves the signal from the load cells, forcing them to regulate their pressure output according to the load measured and effectively regulating the load on the specimen. However it was only later realized that the valves had been supplied configured for internal mode operation and that, to change to external mode, one had to connect the valves to a computer and reconfigure the valves' own software. This arose two possible courses of action: ADFEUP could buy the necessary special adapters to connect the valves to a computer and execute this procedure or could request an intervention by a FESTO technician. The latter option was chosen due to the costs associated with the first. Nonetheless, at the time of writing, said intervention had still not been made and so the VPPX valves are operating in internal control mode.

3.2.3 Air Treatment Unit

The MSB4-AGC:C4:H3:N3-WP Festo service unit (Figure 3.8) was selected instead of the one proposed by Pina, as the previously chosen model was unavailable. It is of equivalent characteristics, namely: an ON/OFF manual valve with silencer, a 5 µm filter (recommended for the cylinders good functioning) with a plastic bowl guard, a manual condensate drain, a pressure regulator ranging from 0.5 bar to 12 bar with a pressure gauge and regulator knob.

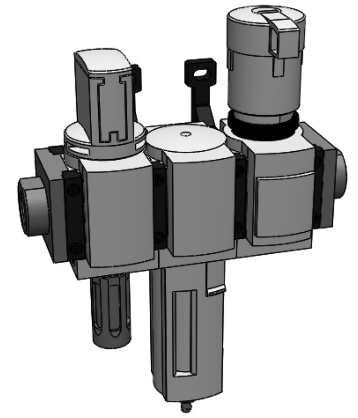


Figure 3.8: Air treatment unit [23].

3.2.4 Directional Valves

A solution using using 5/3 directional valves had been suggested by Pina [5]. However a specific valve had not been selected.

Festo's VUVS-L25-P53C-MD-G14-F8-1-C1 directional valves (Figure 3.9) were chosen. These are in-line 5/3 directional valves. When not actuated they are reset by mechanical springs to their closed mid-position. The 3 positions of the valve allow for the cylinders to move up (by allowing air flow (i.e. pressure) to the lower chamber of the cylinder and connecting the upper one to the exhaust), down (by doing the opposite) or to stand still, thanks to their closed center.

The valves are internally piloted, having a minimum piloting pressure of 2.5 bar and are solenoid-actuated. Their solenoid coils operate at 24 V DC. The valves' size was chosen according to the size and flow rate of the, already purchased, cylinders and VPPX valves.

Figure 3.9: Directional valves [24].

3.2.5 Flow Control Valves

Pina [5] also suggested the use of one-way flow control valves in each chamber to control the flow of the exhaust air. This serves several purposes: in the case of specimen rupture, the flow control valve on the cylinder's lower chamber negates the rupture effects on the air supply lines (possible spikes in pressure, affecting tests taking place in the machine's other stations) and the jerking motion of the cylinder itself; the meter-out design helps reduce stick slip, improving the motion of the cylinders and, by restricting the flow rate of compressed exhaust air, we are effectively regulating the piston speed [25].

Festo's GRLA-3/8-QS-8-D one way flow control valves were selected (Figure 3.10). Their male G3/8 thread allows for direct assembly on the cylinders pneumatic ports and their L shape allows for the cylinders (with the flow control valves) assembly close by each other, directing the pneumatic tubing behind them. On the end not connected to the cylinder the valves have a push-in 8 mm connector. The valves' flow restriction is adjusted via a screw.

Figure 3.10: Flow control valves [25].

3.2.6 Pneumatic Accessories

Along with the main components of the pneumatic circuit, pneumatic tubing, connection and other kinds of acessories were needed to assemble the complete circuit. Table 3.1 resumes the used material which was acquired from Festo.

Table 3.1: Pneumatic accessories

Identification	Model	Qty.	Function
Silencer	UC 1/4	9	Noise reduction at the exhaust ports.
Distribution Manifold	FR-4-3/8	1	Distribution of compressed air from 1 supply line into 3 outlets.
Push-in Fitting	QS-3/8-8	6	Easy connection between G3/8 ports and the 8 mm tubing.
Push-in Fitting	QS-1/4-8	15	Easy connection between G1/4 ports and the 8 mm tubing.

3.2.7 Implemented Circuit

As was already said, the VPPX allow for a control of pressure from 0.1 bar to 10 bar. Despite this, the directional valves need a minimum of 2.5 bar for their internal piloting to function and the valve be actuated.

As we are doing creep tests, our only interest is to control the pressure when the cylinders are applying tension on the specimens, i.e., when they are moving down. Because of this, it was decided to move each VPPX valve downstream from the directional valves, to the line feeding the respective cylinder's upper chamber as depicted in Figure 3.11.

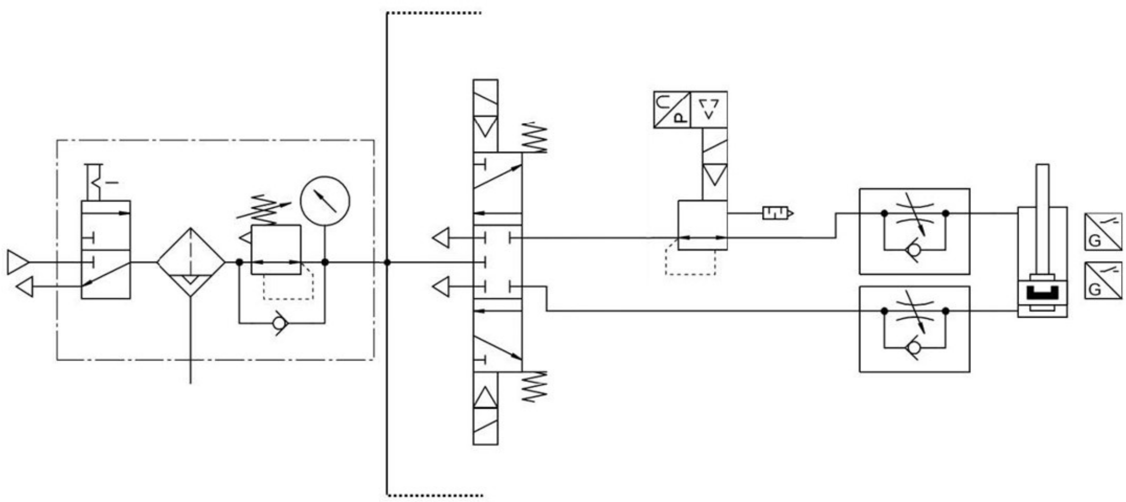


Figure 3.11: Implemented pneumatic circuit scheme.

One could argue that it is desirable to also control the pressure in the cylinder's active chamber when it is moving up. However, by restricting the exhaust air flow from the secondary chamber of the cylinders using the existing flow control valves we are able to limit their ascension velocity. Besides that, as the pressure regulator of the air treatment unit is regulated for 6 bar there is no danger for the cylinders (which can handle up to 12 bar) and not even for the load cells if the system were to fail in such way that the cylinders were exerting compressive forces on these at maximum pressure (the load cells maximum permissible load is about 1.5 times greater than such forces).

The new pneumatic circuit has been assembled and is fully functional. The air treatment unit and the distribution manifold have been adjusted to the lower support frame using standard M8 T-bolts and nuts. A support for the VPPXs and the directional valves has been manufactured according to the schematics in Appendix A.2, upon which they have been mounted.

3.3 Electric Circuit

The electric circuit was the hardware part that required greater intervention. Pina had started its assembly but had not completed it. Aside from the original electrical circuit schematics [5] there was no further documentation of the state of the circuit. On top of that, FEUP's technician which had accompanied Pina's work was not confident that the assembled part of the circuit was in line with said schematics.

Primarily, a thorough revision of the assembled circuit was carried out to ascertain both its (lack of) completion and its corroboration to the schematics. Secondarily, a revision of the schematics was made. Finally, the planned modifications were carried out and implemented. The circuit is now fully assembled and functional, with the exceptions specifically identified along this subchapter.

The first problem identified in Pina's electric schematics [5] was related to his command panel. The machine has three stations that should work independently from each other. In its normal operation, the user has to be able to run a test in a specific station, regardless of the remaining stations' status - whether they are running other tests or standing idle.

Pina proposed a 4 position selector switch to toggle which station was being manually commanded by the user (to set up specimens for example): none, Station 1, Station 2 or Station 3. The problem with this was that the user could unintentionally activate the manual operating mode for a station running a test just by moving this selector switch. Another, more serious, problem would arise if a test was running on Station 2 and the user needed to set up specimens in Station 1 and in Station 3. To change the manually controlled station from 1 to 3, the user would be forced to pass through the Station 2 position, changing this station's behaviour from auto to manual and stopping the running test.

Faced with the costs of acquisition of new electric material to circumvent this problem, ADFEUP felt that there was no need for a physical command panel asides from a ON/OFF switch and an emergency button. It was so decided that all other commands would be given through the computer interface. Besides the two mentioned switches, a "Powered On" and an "Emergency" light indicators were assembled on the front side of the electric cabinet.

The other problems with Pina's schematics were mostly related with signals compatibility between the various subsystems. For a better understanding of this, a schematic representation of a station's components which interact with the electric circuit is now presented in Figure 3.12. In this schematic the arrows represent the flow of information between the various items. It is important to notice that the arrows can represent multiple signals, with different characteristics. The interacting components are further explored along the present chapter, detailing said communications needs and characteristics.

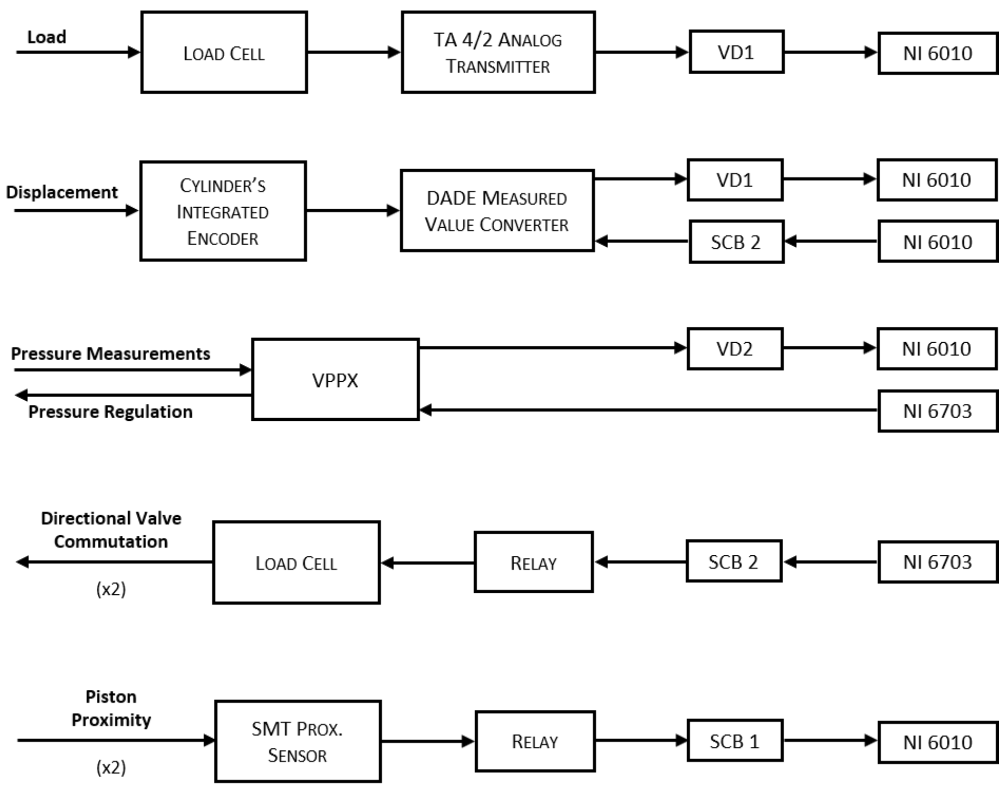


Figure 3.12: Systems interaction and communications of a testing station.

3.3.1 Load Cells and Load Cell Transmitters

As was already said, the machine accommodates, in its upper assembly, three load cells. These are used to measure the forces to which the specimen is subjected. Each TS Load Cell (Figure 3.13) is directly connected to a TA 4/2 Analog Transmitter (Figure 3.14), both components were manufactered by AEP Transducers and had already been previously acquired by ADFEUP.

Figure 3.13: TS Load Cell [26].

Figure 3.14: TA 4/2 Analog Transmitter [27].

Each Transmitter powers the respective Load Cell and receives its signals, converting them. Its output is an analog voltage in the range ±10 V, where +10 V correspond to a tension load of 6000 N and −10 V to a compression load of the same magnitude. The transmitter behaves linearly between these two points, with a linearity error inferior to ±0.02 %. Besides this analog voltage output signal, the transmitter needs to be powered at 24 V DC [26, 27].

3.3.2 Encoders and Measured Value Converters

The cylinders have an integrated linear encoder. Their sinusoidal signals outputs are converted to a DC voltage, in the range 0.1 V to 9.9 V, using a DADE Measured Value Converter - from now on simply referred to as DADE - produced by Festo (Figure 3.15) and also previously acquired.

Similarly to the Load Cell/Transmitter set, the cylinders' encoders directly connect to the DADE. This connection required however three SIM-M12-8GD-5-PU cables from Festo which had not been purchased. The cables were bought and the three connections are working as expected.

Figure 3.15: DADE Measured Value Converter [28].

As we are working with relative displacement encoders, the DADE needs to be referenced whenever power is lost. An additional first commissioning calibration procedure is also required on its first use or if DADE's memory has been reset. For this reasons, the DADE requires several connections besides analog voltage output and power supply. These connections to the electric circuit are summarized in Table 3.2.

Table 3.2: DADE's connections to the electric circuit

PIN	Description	Signal Type	Voltage
1	+24 V power supply	power supply	24 V
2	Measured Signal	analog output	0.1 ... 9.9 V
3	Reference Output	digital output	0 / 24 V
4	0 V Measured Signal	analog output GND	-
5	Reference Input	digital input	0 / 24 V
6	Calibration Input	digital input	0 / 24 V
7	Ready Output	digital output	0 / 24 V
8	0 V power supply	power supply GND	-

The first commissioning procedure is as follows [28]:

Step 1 Switch on the operating voltage.

Step 2 Move the cylinder to the zero point of the work stroke.

Step 3 Set the "Reference Input" for at least 0.5 s.

Step 4 Reset the "Reference Input" signal. As soon as the "Reference Output" is set, the reference point is saved.

Step 5 Move the cylinder to the end position of the work stroke.

Step 6 Set the "Calibration Input" for at least 0.5 s.

Step 7 Reset the "Calibration Input" signal. As soon as the "Ready Output" is set, the work stroke is saved permanently.

Once the first commissioning has been executed, the referencing procedure is achieved by completing steps 1 to 4. In this case, the "Ready Output" signal is set along with the "Reference Output" in Step 4 [28].

After the first commissioning, it is not expected that the DADE's memories are reset. For this reason, after this procedure is completed, the "Calibration Input" terminal will not need to be connected any more. The "Ready Output" shall however be connected to the computer to prevent the cylinder's use in the unlikely event of the DADE loosing its memory. In that case some manual hardware intervention would be necessary for repeating the first commissioning calibration procedure.

At the time of writing, the first commissioning procedure had been completed for Station 3 only for reasons further explored in this chapter.

3.3.3 Pressure Regulator Valves

Each VPPX valve is powered at 24 V DC, outputs an analog signal X, which results from internal pressure measurements, needs a setpoint value W and, when working in external control mode, also needs an external signal representing the measured pressured X_{ext}, as said in Subsection 3.2.2. The valves' electric connections are now summarized in Table 3.3.

Table 3.3: VPPX's connections to the electric circuit

PIN	Description	Signal Type	Voltage
1	Digital communication	no connection	-
2	+24 V power supply	power supply	24 V
3	- Setpoint Value (W^-)	analogue differential input	0 ... 10 V
4	+ Setpoint Value (W^+)		
5	Digital communication	no connection	-
6	Actual Value (X)	analogue output	0 ... 10 V
7	0 V power supply	power supply GND	-
8	External Actual Value (X_{ext})	analogue input	0 ... 10 V

3.3.4 Directional Valves' Solenoid Coils

Each directional valve solenoid needs a 24 V signal to be activated. Six MSSD-EB plug sockets (Figure 3.16) were acquired from Festo and the wiring of said sockets was made in FEUP to save costs of acquiring the plug sockets with the corresponding cables already connected.

Figure 3.16: MSSD-EB Plug Socket [29].

Each solenoid is activated by a relay triggered by a signal from the computer commanding the machine. In Pina's schematics [5], the solenoids responsible for the up movement of the cylinders were activated only by the command panel. As this was eliminated, some relays were repurposed from the discarded circuitry to allow their activation via the computer output.

3.3.5 Travel Limit Switches

Pina had already suggested the use of magneto-resistive proximity sensors to act as travel limit switches [5]. Six SMT-8M-A-PS sensors (Figure 3.17) were acquired from Festo. These sensors are compatible with the cylinders and designed to be assembled in the T-solts on their body. They operate at 24 V, switching their normally open contact when the piston is sensed. The sensor cable has 3 wire connections: the power supply, the power supply ground and the output.

Figure 3.17: SMT Proximity Sensor [30].

Two sensors have been mounted in each cylinder, imposing a safe work stroke. When activated, each sensor triggers a relay, which blocks the corresponding directional valve from allowing more airflow into the relevant cylinder chamber.

Pina had proposed that only the lower limit sensors' signals would be used in the computer yet it was found pertinent to use all six sensors' signals. All corresponding electric connections have been made.

3.3.6 Power Supplies

Most of the machine's subsystems require a 24 V DC power supply to operate.

A MRD-100-24 Mean Well switched power supply had already been acquired - Power Supply 1 (PS1), Figure 3.18. It has a 24 V DC, 4 A output, and the standard single-phase 230 V AC input.

A second linear power supply - Power Supply 2 (PS2), Figure 3.19 - was acquired from BLOCK Transformatoren-Elektronik. The GLS 230/24-3 is a single phase, stabilised DC power supply. This device has a 24 V DC, 3 A output and was acquired to power the DADE, the VPPX valves and the load cell transmitters since linear power supplies are better for avoiding noise related issues in sensor signals. All the remaining systems requiring a 24 V DC supply are powered by PS1.

Figure 3.18: Power Supply 1 [31].

Figure 3.19: Power Supply 2 [32].

3.3.7 Data Acquisition Boards

As we are using a computer to command the machine, we must be able to generate and interpret most of the signals explored so far. In order to attain that, we use a Data Aquisition (DAQ) system. As defined by National Instruments, DAQ "is the process of measuring an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound with a computer" [33].

For the computer to be able to interact with the electric circuit, two DAQ boards had already been acquired: a NI6010 and a NI6703, both manufactured by National Instruments.

The NI6010 (Figure 3.20) is a multifunctional I/O device with 6 single line Digital Input (DI), 4 Digital Output (DO), 16 Analog Input (AI) and 2 Analog Output (AO) channels. Its analog input and output range is −5 V to +5 V.

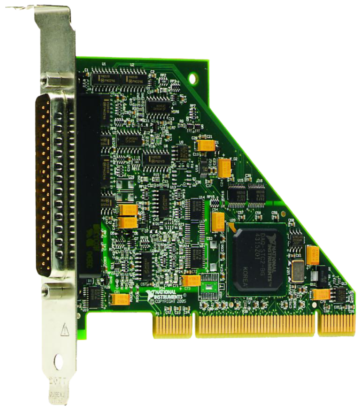


Figure 3.20: NI6010 DAQ board [34].

The NI6703 (Figure 3.21) is an output device featuring 16 Analog Output channels and 8 digital channels that can act as inputs or as outputs. Its analog output range is 0 V to 10 V.

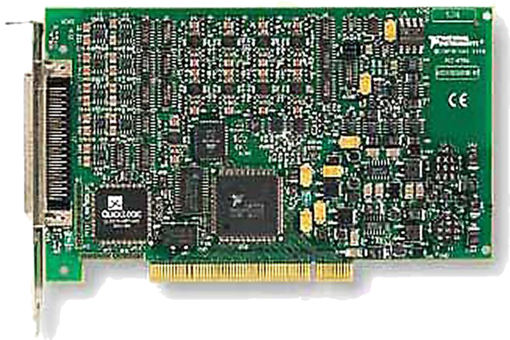


Figure 3.21: NI6703 DAQ board [35].

The digital signals of both devices, as standard in this kind of equipments, are 5 V signals.

As already exposed, in the electrical circuit we have 24 V digital (input and output) signals and analog signals with various ranges that do not correspond to the DAQ boards ranges. Because of that, most of these signals need conditioning.

Pina's DAQ channel assignment had some mistakes and was, in many cases, considered somewhat illogic. Besides this, there were many wrongly connected wires to the DAQ boards that did not match Pina's schematics. Because of this all the DAQ channels were re-assigned from scratch and the corresponding wiring made. One significant aspect of this assignment is that, because we lacked digital input channels, six analog inputs were used for the travel limit switches. On Tables 3.4 and 3.5 each DAQ used channels and the corresponding interacting system can be observed.

Table 3.4: NI 6010 used channels and interacting systems

I/O Device		Interacting System			
Channel	Pin	System	Description	Pin	Terminal
AI GND	25	DADE 1	0 V Measured Signal	4	X12.5
		DADE 2	0 V Measured Signal	4	X12.3
		DADE 3	0 V Measured Signal	4	X12.1
AI 0	1	DADE 1	Measured Signal (Analogue)	2	X12.6
AI 1	21	DADE 2	Measured Signal (Analogue)	2	X12.4
AI 2	22	DADE 3	Measured Signal (Analogue)	2	X12.2
AI 3	5	VPPX 1	Analogue Output X	6	X10.3
AI 4	6	VPPX 2	Analogue Output X	6	X10.7
AI 5	26	VPPX 3	Analogue Output X	6	X10.11
AI 7	28	FDC1	Cyl. 1: Upper Prox. Switch	BK	X9.2
AI 8	20	FDC2	Cyl. 1: Lower Prox. Switch	BK	X9.4
AI 9	2	FDC3	Cyl. 2: Upper Prox. Switch	BK	X9.6
AI 10	4	FDC4	Cyl. 2: Lower Prox. Switch	BK	X9.8
AI 11	23	FDC5	Cyl. 3: Upper Prox. Switch	BK	X9.10
AI 12	25	FDC6	Cyl. 3: Lower Prox. Switch	BK	X9.12
AI 13	7	LCell 1	Load Cell 1: Transmitter	V OUT	X11.1
AI 14	9	LCell 2	Load Cell 2: Transmitter	V OUT	X11.2
AI 15	10	LCell 3	Load Cell 3: Transmitter	V OUT	X11.3
PFI 0/P0.0	13	DADE 1	Reference Output	3	X13.2
PFI 1/P0.1	32	DADE 1	Ready Output	7	X13.1
PFI 2/P0.2	33	DADE 2	Reference Output	3	X13.6
PFI 3/P0.3	15	DADE 2	Ready Output	7	X13.5
PFI 4/P0.4	34	DADE 3	Reference Output	3	X13.10
PFI 5/P0.5	35	DADE 3	Ready Output	7	X13.9
PFI 6/P1.0	17	DADE 1	Reference Input	5	X13.3
PFI 7/P1.1	36	DADE 2	Reference Input	5	X13.7
PFI 8/P1.2	37	DADE 3	Reference Input	5	X13.11
PFI 9/P1.3	19	PC EMER	Emerg. Relay (PC)	-	PC EME

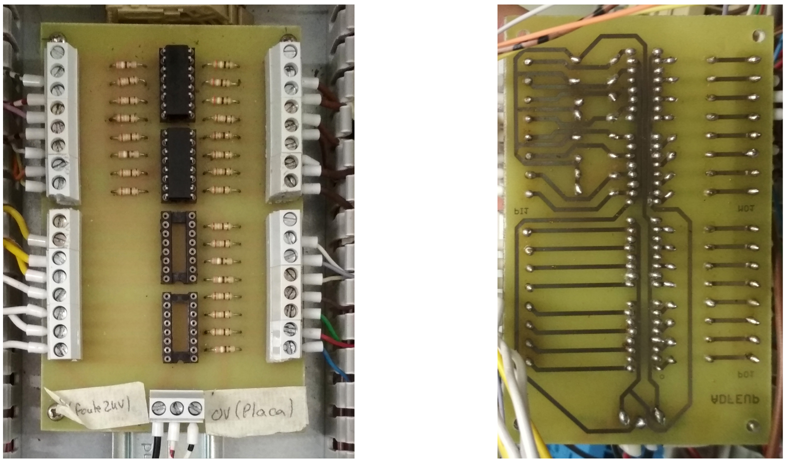
Table 3.5: NI 6703 used channels and interacting systems

I/O Device		Interacting System			
Channel	Pin	System	Description	Pin	Terminal
AO 0 (V)	34	VPPX 1	Analogue Input $W+$	4	X10.2
AO GND 0	68	VPPX 1	Analogue Input $W-$	3	X10.1
AO 1 (V)	66	VPPX 1	Analogue Input X_{ext}	8	X10.4
AO 2 (V)	31	VPPX 2	Analogue Input $W+$	4	X10.6
AO GND 2	65	VPPX 2	Analogue Input $W-$	3	X10.5
AO 3 (V)	63	VPPX 2	Analogue Input X_{ext}	8	X10.8
AO 4 (V)	28	VPPX 3	Analogue Input $W+$	4	X10.10
AO GND 4	62	VPPX 3	Analogue Input $W-$	3	X10.9
AO 5 (V)	60	VPPX 3	Analogue Input X_{ext}	8	X10.12
P0.0	2	EMERG	Emergency Button	-	X5.1
P0.1	3	DV 1 UP	Directional Valve 1: UP	-	X8.2
P0.2	4	DV 1 DWN	Directional Valve 1: DOWN	-	X8.6
P0.3	5	DV 2 UP	Directional Valve 2: UP	-	X8.3
P0.4	6	DV 2 DWN	Directional Valve 2: DOWN	-	X8.7
P0.5	7	DV 3 UP	Directional Valve 3: UP	-	X8.4
P0.6	8	DV 3 DWN	Directional Valve 3: DOWN	-	X8.8
D GND	36	-	Signal Conditioning Boards GND	-	-
+5 V	1	-	Signal Conditioning Boards +5 V	-	-

3.3.8 Signal Conditioning Circuits

A circuit board designed for digital conditioning already existed (Figure 3.22). This conditioning circuit has 16 channels that allow the conversion of digital signals between the computer and the corresponding 24 V interacting system. Half the channels for computer output (PC OUT) signal conditioning and half for computer input (PC IN) signal conditioning.

The PC OUT channels, when presented with a high signal in the terminal connected to the DAQ board, connect the corresponding pin of the 24 V interacting system to the ground terminal. This allows for relay triggering, for example, connecting one coil terminal to a power source, and the other to the PC OUT terminal. The circuit will only be closed when a high signal is given by the computer on the respective channel and so that is when the relay is activated.



(a) front (b) back

Figure 3.22: Signal Conditioning Board 1.

The PC IN channels, when presented with a high signal in the terminal connected to the 24 V interacting system, output 5 V in the corresponding pin connected to the DAQ system.

This circuit board has revealed to be of low quality manufacturing. Although having been resoldered several times during the course of this work, some channels' behaviour is still unreliable. In addition to this, the board does not have enough channels for the necessary digital signal conditioning and presents no analog channels.

A unique signal conditioning board, capable of doing all the needed signal conversions, was planned. As, at the time of this dissertation, said board could not be manufactured in FEUP with the desired characteristics, smaller, independent circuits manufacture and implementation was carried out for the remaining signal conditioning.

It is important to notice that this existing (unreliable) board was not replaced because it is expected, in the near future, that the fabrication of the desired board to do all the signal conditioning becomes possible in FEUP.

Pina already demonstrated that using a voltage divider to convert the 0-10 V analog signals from the DADE to a 0-5 V range would not cause any loss of resolution [5].

The VPPX control range is from 0 to 10 bar. The 16 bit resolution of the DAQ output for this system, working with its 0 V to 10 V signal, can be calculated by

$$\frac{10}{2^{16}} = 0.000\,15\,\text{bar} \tag{3.3}$$

As half of this is still vastly greater than the VPPX input resolution we have no loss of resolution here too.

As the Load Cell Transmitter output is from $-10\,\mathrm{V}$ to $+10\,\mathrm{V}$, and the analog input range of the DAQ board from $-5\,\mathrm{V}$ to $+5\,\mathrm{V}$, we also have to use a voltage divider here.

Two standard voltage dividers were manufactured acording to the shematics in Appendix B (pages 18 and 19), have been connected to the system and are functioning as intended. Voltage Divider 1 (Figure 3.23) halves the tension of the signals from the DADE and from the Load Cell Transmitters and Voltage Divider 2 (Figure 3.23) does the same operation for the VPPX analog output signals.

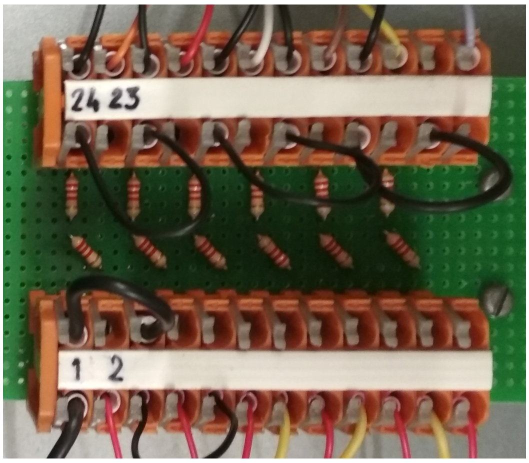


Figure 3.23: Voltage Divider 1.

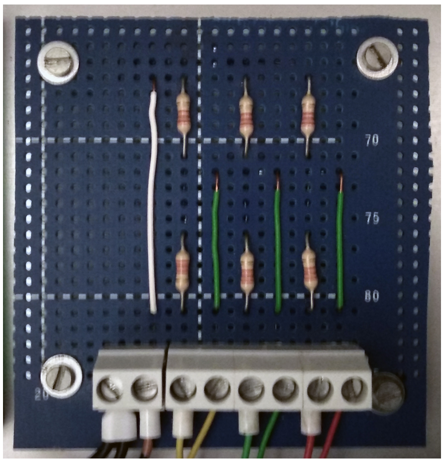
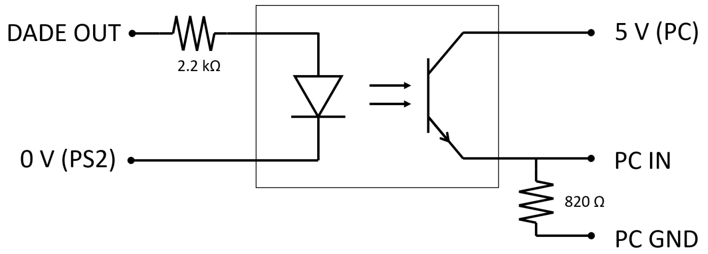


Figure 3.24: Voltage Divider 2.

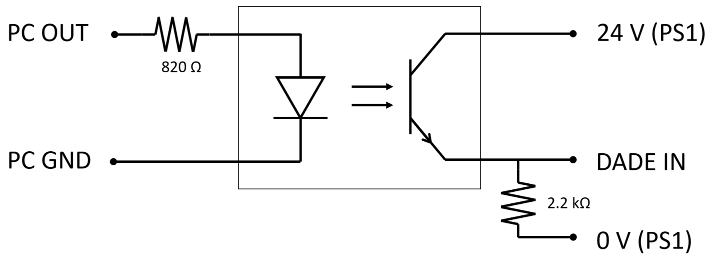
Some signal conditioning was still needed for the remaining digital signals. As 24 V to 5 V (and vice-versa) conversion is a common need in electric circuitry nowadays, a commercial available solution was approached. Two DST-1R4P-N boards were acquired from the Chinese manufacturer Alzard Automation. Despite their very low cost and the fact that, when tested with a multimeter, the boards were showing the expected behaviour, when connected to the DADE, these boards would not function correctly for unknown reasons (insufficient drive current is a possible (not confirmed) explication).

A new schematic was designed for a in-house manufacturing of this new signal conditioning board (Appendix B, page 20). This new board (Signal Conditioning Board 2) works slightly differently from the existing one, as the DADE requires not a connection to the ground to close the circuit but a 24 V signal in its digital inputs. It has four PC OUT and eight PC IN channels. In Figure 3.25 we can see a scheme showing a PC IN and a PC OUT channel of this new circuit.

This design was tested with identical components using a prototyping breadboard, borrowed from one of FEUP's laboratories (Figure 3.26). Once proven that the board functioned as desired, the circuit for the needed signal conditioning was implemented



(a) PC IN



(b) PC OUT

Figure 3.25: Signal Conditioning Board 2 Schemes.

on this breadboard for Station 3 only, pending the manufacturing of Signal Conditioning Board 2.

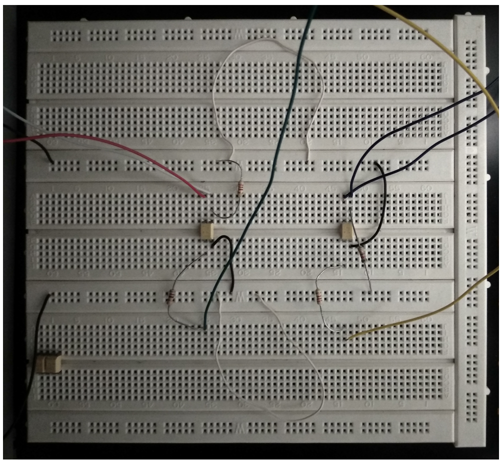


Figure 3.26: Prototype circuit.

Altough the components to manufacture Signal Conditioning Board 2 are relatively simple and easy to acquire (a standard matrix board, some terminal blocks, PCB sockets, optocouplers and resistances), the process for material funding and aqcuision is not. Because of this, it was not possible, up until the time of writing, to produce this board. Therefore, only Station 3 is functional.

All the remaining electric circuit has been implemented and tested. All the wiring connections have been made and are ready to receive this missing board, upon installation of which the circuit will be fully functional. It is important to notice that it is still necessary to carry out DADE 1 and DADE 2 first commissioning procedures. In Figure 3.27 the cabinet containing the electric circuit can be seen.

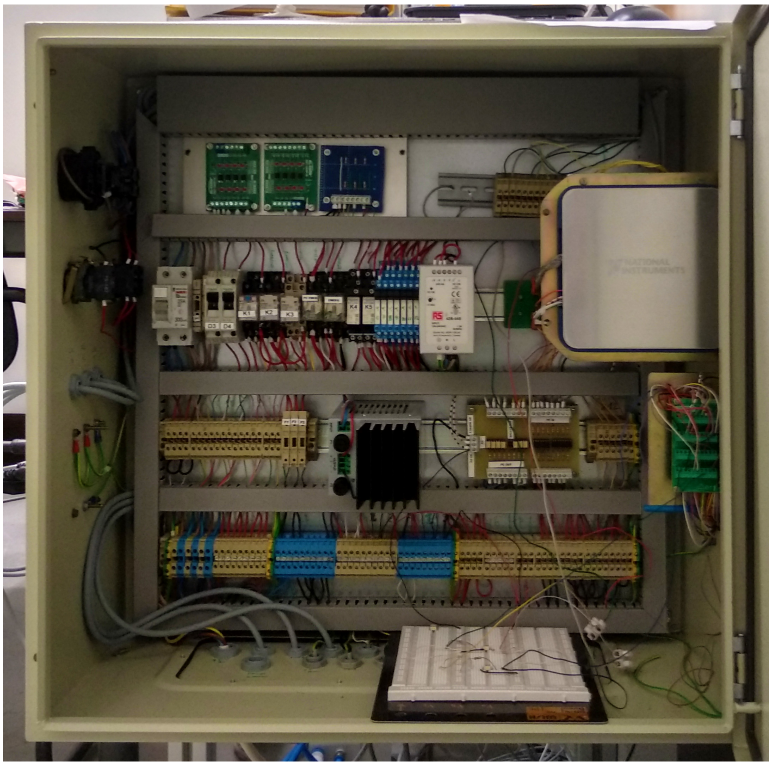


Figure 3.27: Electric cabinet.

3.4 Discussion

Pina's mechanical components of the machine have been assembled. Asides from some screws and bolts, the only missing parts were the grips' springs, which have been calculated and bought, and an extension rod (for each station), which has also been manufactured.

The missing pneumatic components were chosen and purchased. The pressure regulator valves were moved downstream from the directional valves because the latter have a minimum piloting pressure which would reduce the pressure regulation range unnecessarily. The entire pneumatic circuit has been assembled and tested, and it is fully functional.

The physical command panel was eliminated. All commands to the station will now be given through the computer. A linear DC power supply was acquired to power the

DADE, the VPPX valves and the load cell transmitters. All the DAQ devices' channels have been re-assigned and rewired. Two voltage dividers were manufactured to make possible the analog communications between the various systems and the computer. A digital signal conditioning board is pending fabrication, its design having been previously tested. A prototyping board is being used to make possible the operation of Station 3 while this digital signal conditioning board is not fabricated. All the remaining circuitry has been assembled and tested and it is fully functional.

Chapter 4

Software and System Behaviour

The machine is commanded and supervised by a computer. This chapter addresses the implemented software and simultaneously the system behaviour as they are intrinsically dependant on each other. Although some specific perks of the programming will be brought to attention, instead of dwelling into the details used to program the system behaviour, the software analysis will be mostly a functional one.

4.1 NI LabVIEW

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a programming language developed by National Instruments.

Unlike the conventional programming languages, LabVIEW is a graphically based programming language. Every LabVIEW programming element, called Virtual Instrument (VI), has two main components, displayed in separate windows: a front panel and a block diagram. The front panel is where the controls and indicators are displayed, where the user interacts with the program. The block diagram is the source code of the VI. That is, the ambient which contains the programming behind the front panel to actually make it do something [36].

LabVIEW was chosen as the programming language because of two main reasons. The fist is that the DAQ boards were manufactured by National Instruments, and LabVIEW has VIs that facilitate the programming involving such boards. The second is that there is already other testing equipment used by ADFEUP programmed in LabVIEW, and so, the researchers of this group are already comfortable using this software.

Pina [5] made some suggestions regarding the Graphical User Interface (GUI) and experimented a bit with the front panel but did not program much on the block diagram. For this reason, his software would not accomplish anything on the hardware, and so it was not used. All the programming implemented in the machine was entirely developed by the author of the present dissertation.

4.2 System Behaviour Overview

The system was designed to work as an independent state machine for each station. Each state is the program waiting for something: for an event to be detected or actions to be completed. The events can be external to the coding (for example the activation of a relay) or internal (for example a timer inside certain state) [36].

Our machine has 8 possible states (for each station) that are briefly presented in Figure 4.1. Every state acts as a diferent screen for the user to interact with and can contain multiple sub-states and actions. Each state's behaviour and programming will be explored in detail along this chapter.

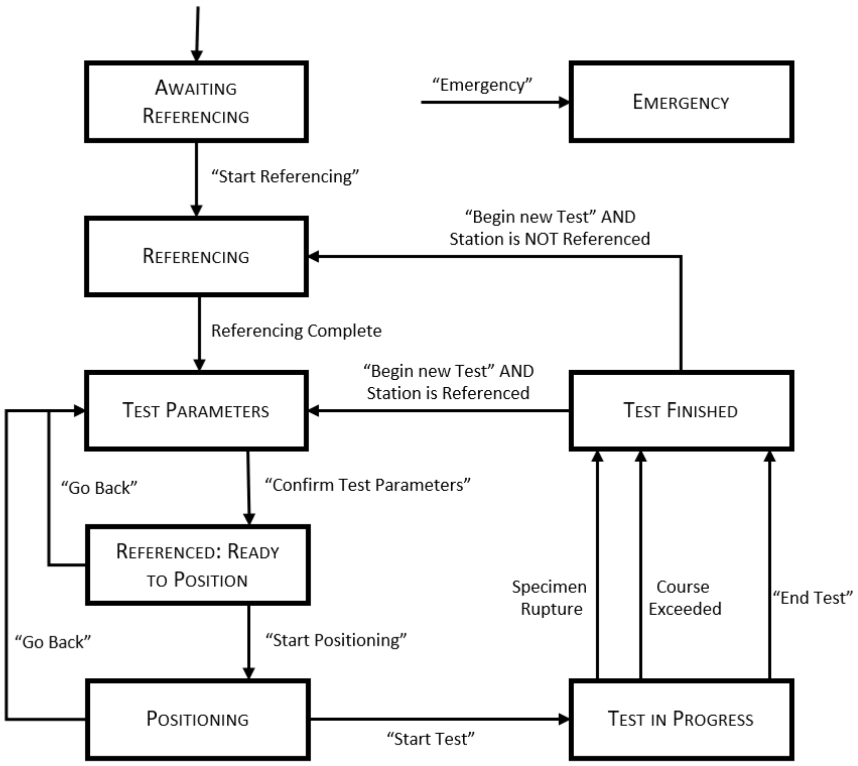


Figure 4.1: General station behaviour.

Because, at the moment of writing, only Station 3 is functional (as explained in Section 3.3) the program was only implemented for this station. It was however developed with the three stations in mind and coded in a way that makes easy the implementation of the remaining two. For now, we will focus on Station 3, noting the required adaptations for the implementation of the software to the remaining stations along the way.

Our main program runs inside a case structure nested in a while loop. The loop allows the code to run continuously, while the case acts as the "state" for our state machine. Every time the loop is ran, the code inside the active case is also ran. The input condition for the case structure is given via a shift register, this logs an output condition from the previous loop and feeds it as an input. In Figure 4.2 an example of this kind of structure is shown. In this case, the loop would run continuously in the "Awaiting Calibration" state, as the shift register (the blue symbol, with the arrow) is continuously being fed this value.

Also inside this while loop, but outside the case structure we have the DAQ assistant tasks. These update local variables with the DAQ boards' inputs or the DAQ boards' outputs using local variables. Each local variable is associated to a control or indicator. Some of these for the user to interact with, others, hidden from the user, to merely function as auxiliary variables.

To make the program work with the two remaining stations, one would simply have to create a second and a third case structure inside the while loop; to associate these with two new, separate, shift registers; copy the code inside the implemented case structure to the new ones, changing variables accordingly (all local variables associated with Station 3 were coded with the prefix "ST3"). As new local variables have to be created, one simply has to change this prefix to refer to the appropriate station and add the new local variables to the DAQ assistant tasks, reconfiguring the latter accordingly.

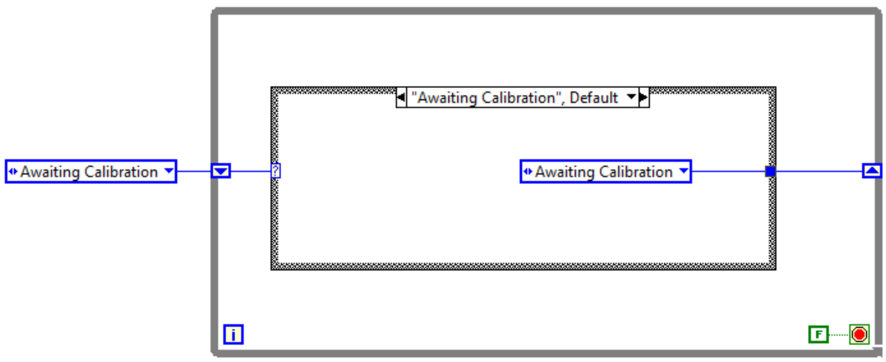


Figure 4.2: A case structure nested in a while loop.

4.3 DAQ Assistant

LabVIEW has some built-in VIs to facilitate the programmer's work. One of these is the DAQ Assistant Express VI. After a simple initial configuration (Figure 4.3) made through an assistant that LabVIEW automatically opens once we place the DAQ assitant block, the code for the acquisition of signals using DAQ boards is automatically generated and incorporated in a single block with simplified inputs and outputs.

The configuration includes the indication of which channels we are acquiring the signals from, when we are acquiring them (every time the block is run, continuously at a fixed acquisition rate, or even just once), the voltage range of these signals, their terminal configuration and other parameters, like custom scaling and advanced triggering options.

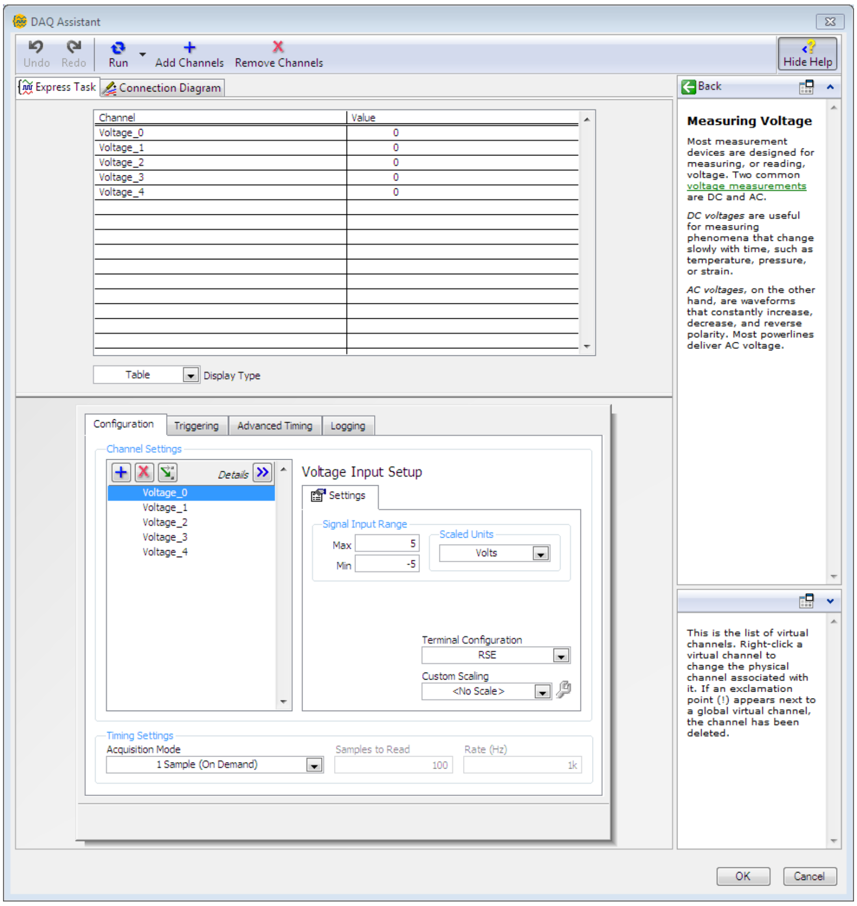


Figure 4.3: DAQ assistant configuration window.

Because of the way LabVIEW runs its code, every DAQ assistant can only perform signal input or signal output. There cannot be multiple DAQ assistants, associated with the same DAQ board, executing similar tasks (i.e., reading AI, reading DI, writing AO or writing DO) and so, these must be combined in the same assistant. In Figure 4.4 we can see the DAQ assistants currently in use.

The first DAQ assitant handles the analog inputs connected to the NI6010 board. The block output is in the form of Dynamic Data (indicated by the thick blue line), this means that the data not only contains the voltage information but also time information. The

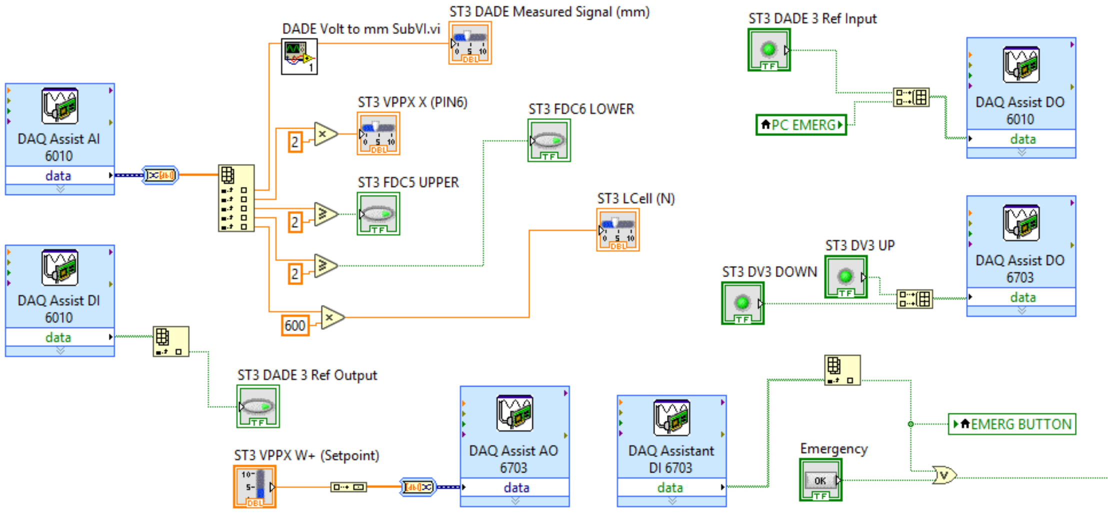


Figure 4.4: DAQ assistant blocks and connections.

block connected to it is a Dynamic Data Converter. All it does is striping the time information from the data, outputting an array of voltages (thick orange line). Now we need to use an Index Array block to separate the elements of this array, because every one is a different analog input to the computer (orange thin lines). The first element is the measurement signal from the DADE. This analog voltage is converted using a custom Sub-VI created for the effect. Simply putting it, a Sub-VI is a program within a program. In this case all it does is the necessary arithmetic operations to convert the voltage signal from the DADE into millimetres. This value is then associated with the local variable *ST3 DADE Measured Signal (mm)*. The signal from the analog output of the VPPX valves is numerically equal to half of the measured pressure in bar and so only needs to be mutiplied by two before its association with the local variable *ST3 VPPX X (PIN 6)*. As we are using analog inputs for the travel limit switches, we are checking if the voltage is higher than 2 V and saving this logic value to the local variables *ST3 FDC5 UPPER* and *ST3 FDC6 LOWER*, respectively. To convert the voltage signal from the Load Cell Transmitter, one has to multiply this value by 600 (the load cell transmitter outputs 10 V with a load of 3000 N and 0 V at 0 N, behaving linearly between these points, but the voltage from the transmitter is being halved by Voltage Divider 1 before entering the DAQ board). The load cell value, in Newtons, is then associated to *ST3 LCell (N)*.

The second DAQ assistant handles the digital input of the NI6010 board. Even though we only have one signal of this type, the block output is still an array of logic values (green thick line). The single existing element of this array still needs to be extracted with an Index Array block, after which it is linked to the *ST3 DADE 3 Ref Output* local variable.

Another DAQ assistant handles the digital input of NI6703. This contains only one signal, coming from the emergency relay triggered by the emergency button. Similarly to the exposed on the previous paragraph, the element is extracted from the array and output to a local variable (*EMERG BUTTON*). This is a special input to the computer because, unlike the others, which are all associated only with local variables used in other parts of the programming, this is also directly connected to blocks performing override operations of certain variables. This will be explored in greater detail in Section 4.12.

The outputs of the computer need the inverse operation of the processes described so far, i.e., the separate elements, originating from local variables need to be combined into arrays before entering the respective DAQ Assist block. This is done using Build Array blocks.

4.4 Graphical User Interface

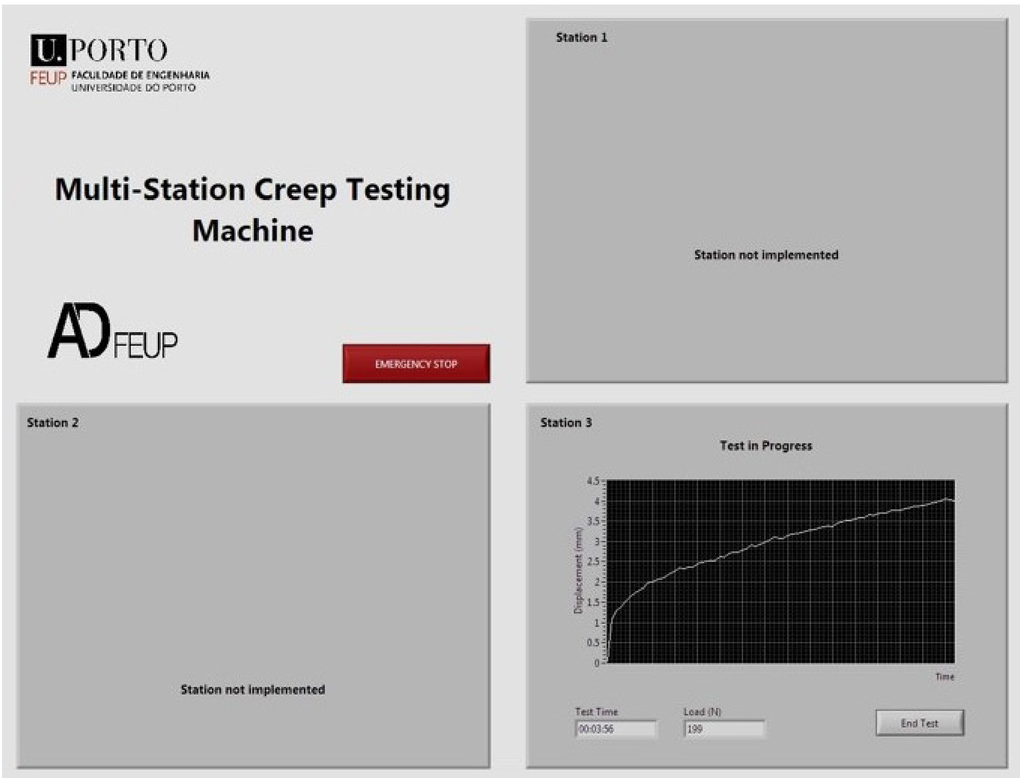


Figure 4.5: Graphical User Interface.

As already hinted, the user only interacts with the front panel. Our GUI consists in a screen divided into three panes: one for each station. Even though the three panes are always displayed, each of them is completely independent from the others and their size still allows for a comfortable monitoring of each station. In addition to the physical emergency button the user also has, in his screen, at all times, a virtual emergency button that behaves similarly.

Each pane changes according to the relevant state of the corresponding station. In Figure 4.5 we can see the general look of the interface in a situation were Station 3 is performing a creep test. All the panels' different displays will be presented in detail along the exploration of the machine's states in the following sections. As the remaining GUI will remain unchanged, said presentations will be focused on the panel itself, though the computer screen will always be displaying the three stations.

4.5 State: Awaiting Referencing

"Awaiting Referencing" is the default state of our state machine. This means that on the first loop, the state machine will start here, independently of previous values for the various variables.

This is one of the simpler states of the machine. As the it has just been turned on, the DADEs need referencing. In this state, as we can see in Figure 4.6, the computer is only awaiting for the user command to enter the next state, "Referencing", where said procedure will be completed.

This state is also used to reset some of the used local variables, as shown in the block diagram in Figure 4.7.

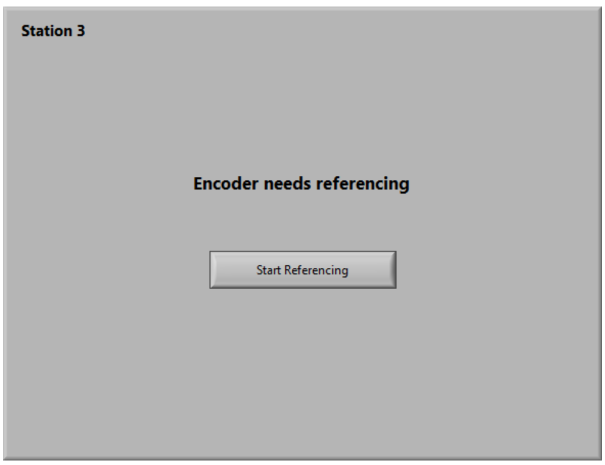


Figure 4.6: "Awaiting Referencing" GUI.

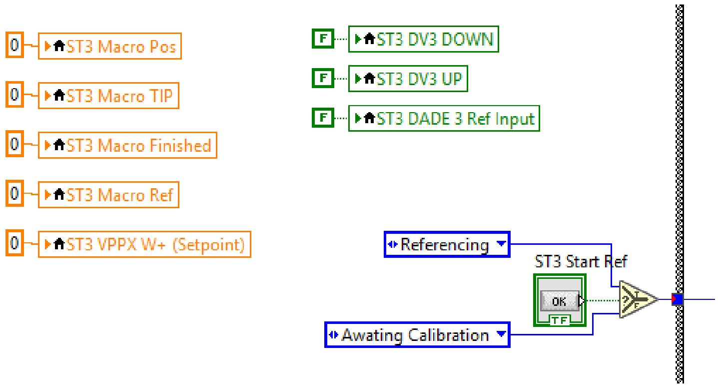


Figure 4.7: "Awaiting Referencing" block diagram.

4.6 State: Referencing

The "Referencing" (sub)state machine has 4 states (Figure 4.9). It starts in State 0, were it is assured that the directional valve is closed. Once the user confirms that the station is clear by pressing the button on the interface (Figure 4.8), the machine transits to State 1. Here the VPPX pressure is set to 3 bar and the solenoid on the directional valve is actuated, allowing airflow into the upper chamber of the cylinder. Once the lower travel limit switch is triggered, the machine moves to State 2, the VPPX setpoint is set to 0 bar, the directional valve disengaged and the DADE Reference Input set to high. After 0.5 s the machine changes to State 3, resetting the DADE Reference Input. If the DADE Reference Output is high, indicating that the referencing procedure was successful, the global state machine transits to the next state: "Test Parameters". If after 2 s this signal is not present, the machine will attempt again to execute the referencing procedure, transiting to State 0 and awaiting again for the user confirmation that the station is clear.

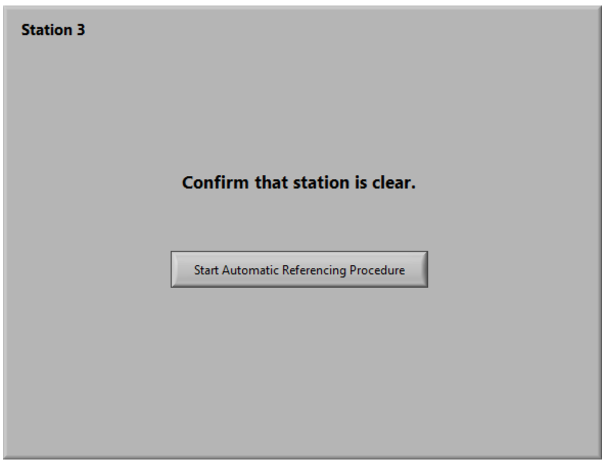


Figure 4.8: "Referencing" GUI.

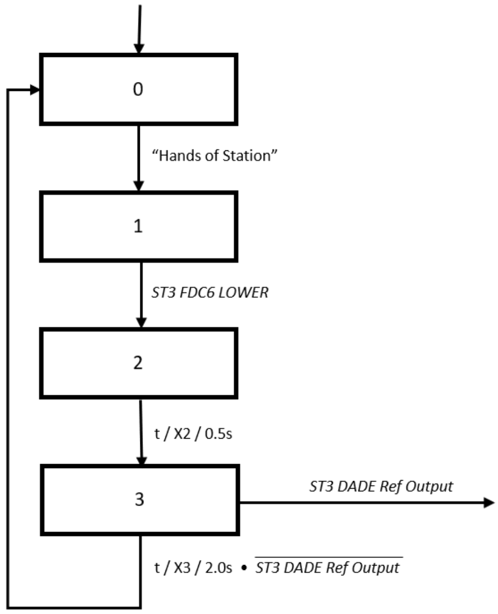


Figure 4.9: "Referencing" state machine.

4.7 State: Test Parameters

In this state, the software awaits for the user to input the test parameters: the desired load and sample rate (Figure 4.10). The desired load input coerces the user to introduce a value between 100 N and 2800 N, these being the limits at which the machine can perform creep tests, and the sample rate input requires a positive value. Once the user presses the "Confirm Test Parameters" button, the machine transits to the "Referenced: Ready to Position" state.

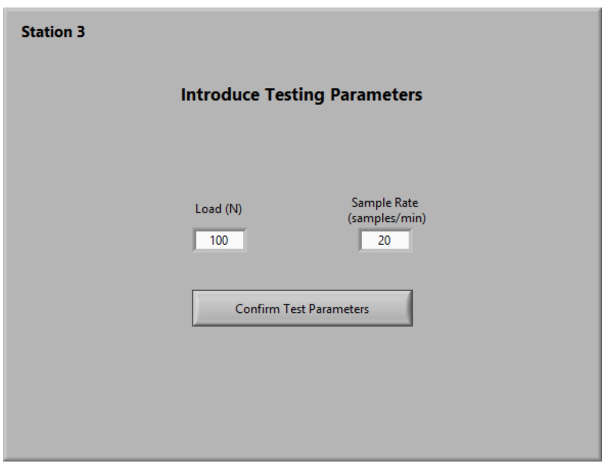


Figure 4.10: "Test Parameters" GUI.

4.8 State: Referenced: Ready to Position

The user is now faced with a screen were the previously input load and sample rate are displayed. If he agrees with the values he can proceed to the "Positioning" state. If he realizes that something is wrong he can go back to the "Test Parameters" state.

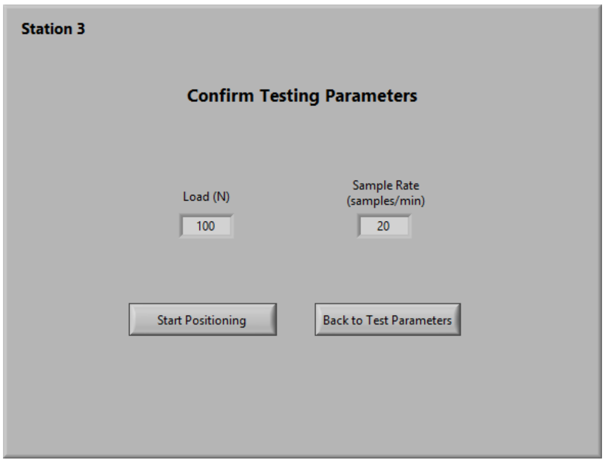


Figure 4.11: "Referenced: Ready to Position" GUI.

In LabVIEW, one can have various behaviours when using buttons. In the previous states, the buttons were ordered to "Latch Until Released", this made them automatically reset their status. Now, because of the way the code is ran inside LabVIEW, and because we have multiple buttons, we were forced to make them "Switch When Pressed". Because of this, two Property Node blocks (Figure 4.12) were employed to assure that the buttons start the state in the "unclicked" status, even if the user has gone back to the "Test Parameters". This was used for many other buttons in the forthcoming states but because it is a simple programming detail it will not be brought to attention again.

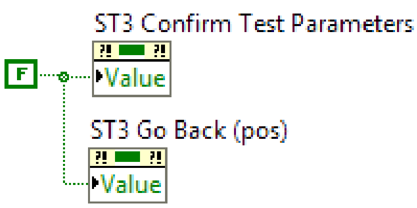


Figure 4.12: Property Node blocks.

Besides the Property Nodes, only the blocks needed for the behaviour explored in the previous paragraph -which do no more than displaying the local variables associated with the previous inputs and outputting to the shift register the appropriate value when one of the buttons is pressed- were programmed in this state.

4.9 State: Positioning

In this state the machine will position its lower claw for the user to mount the specimen and provide the options to zero the load cell and the position measurements. This is achieved through the use of a state machine with 7 states, through a process which resulted from experimental tweaking of the different parameters involved. This process makes use of the remaining pressure in the cylinder, held by the flow control valves, to accomplish a reasonable positioning of the system.

It is important to keep in mind that, because of the alterations of the pneumatic circuit discussed in Section 3.2.7, the pressure in the lower cylinder chamber cannot be controlled, that air is a compressible fluid which makes position control of pneumatic mechanisms an extremely difficult task and that this process is just a, somewhat simple, way discovered to achieve a positioning of the station's claw with acceptable precision and repeatability for the desired objective that is to allow the specimen emplacement and fixation.

In Figure 4.13 we can see the GUI at different steps of the "Positioning" State. The present state of this (sub)state machine is given via the local variable *ST3 Macro Pos*, feeding into a case structure. These states, which are also presented in the form of a diagram in Figure 4.14, are now summarized:

State 0 The directional valve is set to its closed state and the VPPX valve setpoint is set to 0 bar. Property Nodes are used to disable and grey out the "Go Back" and "Start Test" buttons. The display on top of the panel is coloured dark green with "Wait" written on it (Figure 4.13 (a)). Once this is complete the station enters State 1.

State 1 The VPPX valve is open to the maximum and the directional valve is set to allow airflow to the upper chamber of the cylinder. This will pressurize this chamber at 6 bar (pressure imposed by the Air Treatment Unit). After 400 ms[1] the station moves on to State 2.

State 2 The VPPX setpoint is reset and the directional valve is ordered to allow airflow into the lower chamber. Because the flow control valves are restricting the airflow out of the upper chamber, we are creating a counter-pressure impeding the cylinder from moving up too fast, even if the lower chamber is at maximum pressure. Once the DADE measured position is greater than 151 mm minus the desired claw distance[1] - which the user can set via a control on screen, locked to accept an input between 15 and 200 mm -, the station enters State 3.

State 3 The VPPX is again open to the max and the directional valve ordered to allow airflow to the upper chamber, re-establishing a counter-pressure oposing the ascending movement of the cylinder. After 500 ms[1], the station moves on to State 4.

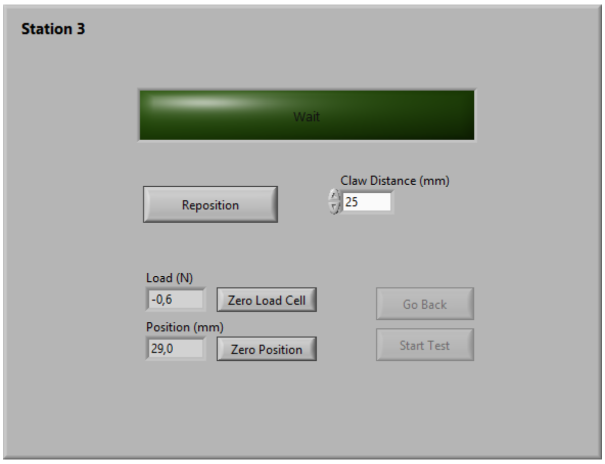
State 4 The directional valve is disengaged, making it move to its closed center position and blocking the airflow from and to the chambers (minus air leakages). As the chambers are pressurized at approximately the same pressure, but the piston area is greater on the lower chamber, the cylinder will, slowly, continue to move up, until the forces are equalized. For this to happen at the desired position (with a precision of about 5 mm), the directional valve is instantaneously actuated to allow airflow into the upper chamber if the sum of the DADE measured value and the desired claw distance is greater than 254 mm[1] or if the upper travel limit switch is actuated. At any point during State 4 the user can re-adjust the desired claw distance and order the positioning process to restart (ordering the station to go to State 5) via the corresponding controls available on screen. The load and the measured position can also be zeroed at any point during State 4 - this was a requirement of ADFEUP- which is achieved by saving offset values to local variables when the corresponding buttons are pressed. The load measured value and the cylinder position (minus their offset values) are displayed at all times. 15 seconds[1] after the sum of DADE measured value and the desired claw distance reaching 190 mm[1], the station has reached an equilibrium and has stopped moving. For this reason, the display on top of the panel changes to light green and displays the message "Place Specimen", and the "Start Test" and "Go Back" buttons are now enabled (Figure 4.13 (b)). If the user presses the "Go Back" button, the station will return to the "Test Parameters" state. If the user presses the "Start Test" button, the station moves on to State 6.

State 5 The "Reposition" button has just been pressed. The directional valve is set to allow airflow into the upper chamber and the VPPX set to 3 bar, making the cylinder descend. The "Start Test" button is disabled and greyed out and the display reverted to the dark green with "Wait" written status. Once the lower travel limit switch is activated, the station moves to State 0.

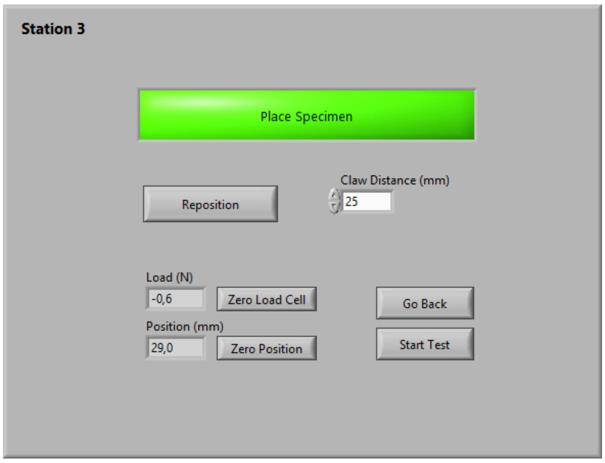
State 6 The "Start Test" button has been pressed and the machine makes its last preparations before commencing the creep test (Figure 4.15). Some local variables are reset and the saved data file generation starts: first a line registering the date and

[1] Values experimentally obtained.

time at which the test begins is saved to a text file on the desktop (ADFEUP is used to use this kind of files with their testing machines), followed by a line containing the headers of the variables which will be registered, namely "Elapsed Time (s)", "Measured Load (N)", "Desired Load (N)" and "Position (mm)". Once this is complete, the station transits to the "Test in Progress" state.



(a) Station Positioning



(b) Ready to Place Specimen

Figure 4.13: "Positioning" GUI.

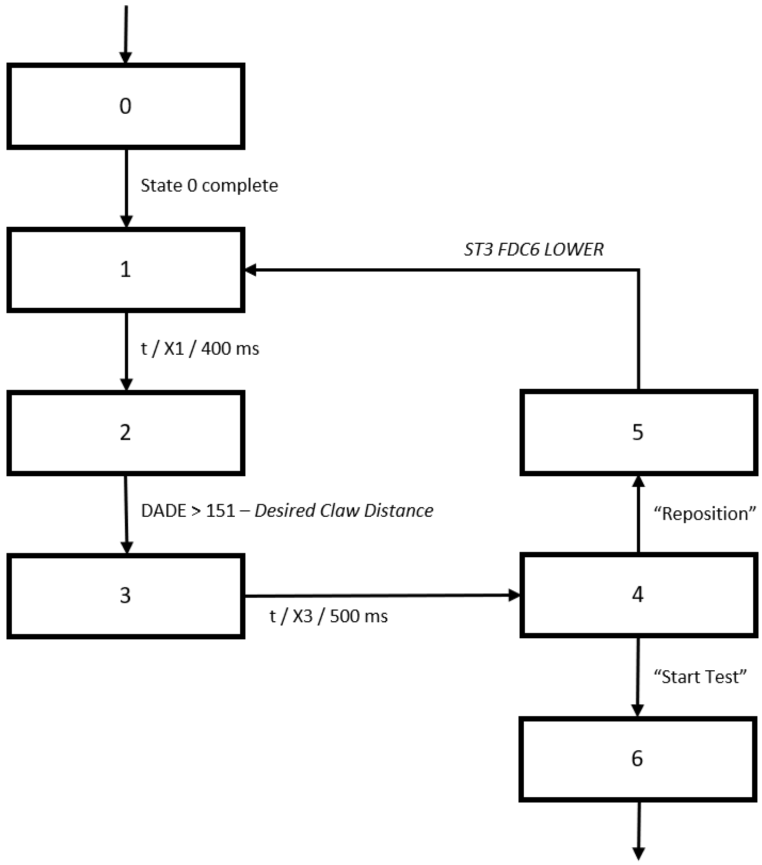


Figure 4.14: "Positioning" state machine.

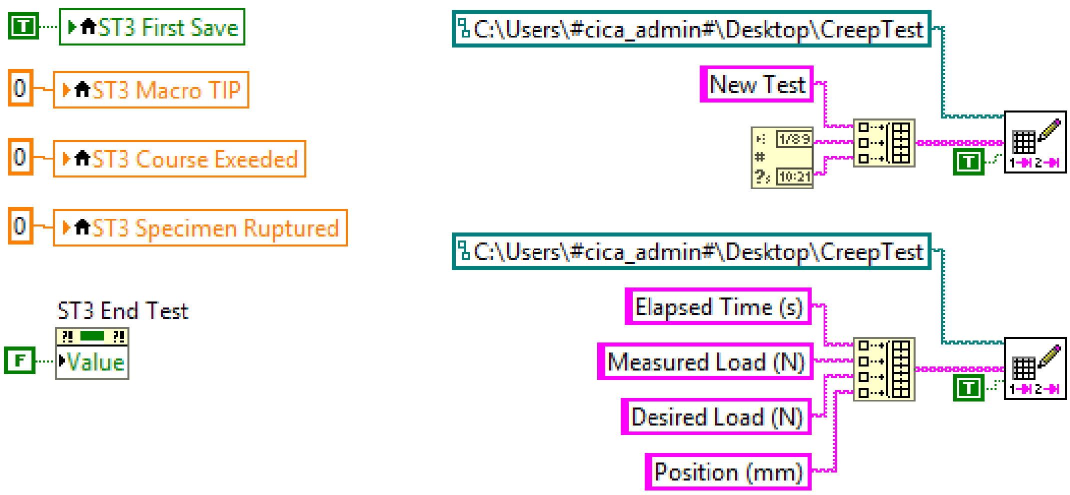


Figure 4.15: Final pre-test preparations (block diagram).

4.10 State: Test in Progress

This is the state where more simultaneous and distinct actions occur. In this state, the GUI displays a chart showing the displacement as a function of time, displays the test time, the measured load and also a button allowing the user to end the test (Figure 4.16). The first time the loop is ran with the machine in this state, the inicial values are appended to the file started in "Positioning" (State 6), the chart is reset and the test timer started.

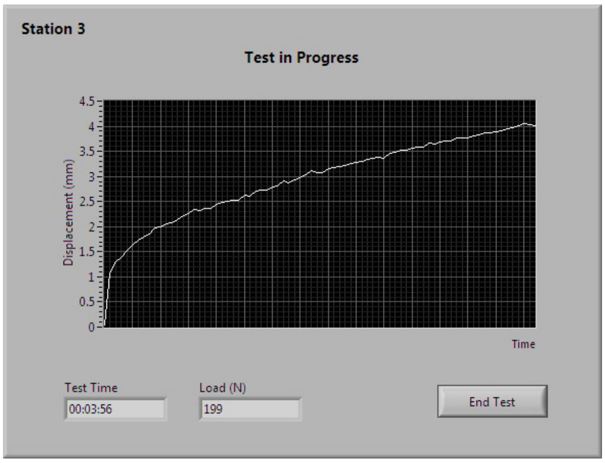


Figure 4.16: "Test in Progress" GUI.

The "Test Time" and the (measured) "Load (N)" displays are updated in real-time, every time the system while loop runs. The chart display however is updated only according to the sample rate introduced by the user in the "Test Parameters" state. When this happens, the "Elapsed Time (s)", "Measured Load (N)", "Desired Load (N)" and "Position (mm)" values, at that moment, are also appended to the saved data file.

The software was programmed like this because LabVIEW charts are limited to 1023 data points. If this value is surpassed, the graph starts shifting to the left substituting the older values. Besides that, adhesive joints creep tests can vary greatly in length, lasting from a few minutes to several months. It makes no sense to have the same data saving rate for such divergent durations, and the user is the one who best can adjust this, according to the material in study and the desired data results.

It is important to notice that even if the 1023 point limit is exceed and the older values are not displayed in the chart during testing, these remain saved in the file, which is virtually only limited by the space available in the hard drive and the file system used by the operating system. For example, a test left running for just over 16 h, with a sample rate of 5 samples/minute generated over 4800 sets of saved data and resulted in a file under 170 kB. We can extrapolate this, and for a 2 GB file -which is a file comfortably handled by most modern computers- we would get almost 60 million sets of data, a colossal array for standard creep tests and analyses.

Even if its not important to save data as often in a three month test as in a three minute test, it is still important to monitor the machine status as close to in real-time as possible. Besides the update of the "Test Time" and "Load (N)" displays and the data saving, all the software mentioned in this sub-chapter is working in real time, except specifically indicated.

Ideally we would use the load cell measured value to control the pressure in the upper chamber and to correct it continuously. As the VPPX valves are still operating in internal mode we will be working in an open loop (although not completely, because the cells have an internal closed loop controller). We are going to be giving a constant reference to the VPPX valves which will translate into a determined load on the specimen. Theoretically one could relate the pressure in the cylinder's chambers with the force measured by the load cell, taking into account factors like the piston's areas, the lower assembly weight and the expected friction forces. Because these factors can vary non linearly and because it would be easy to leave out factors which could unknowingly also have an impact in this relation, an experimental approach was taken: the station was put in function with a material of negligible deformation (under the applied loads) and the pressure in the VPPX varied, whilst the forces measured by the load cell and the setpoint value of the VPPX were monitored and saved.

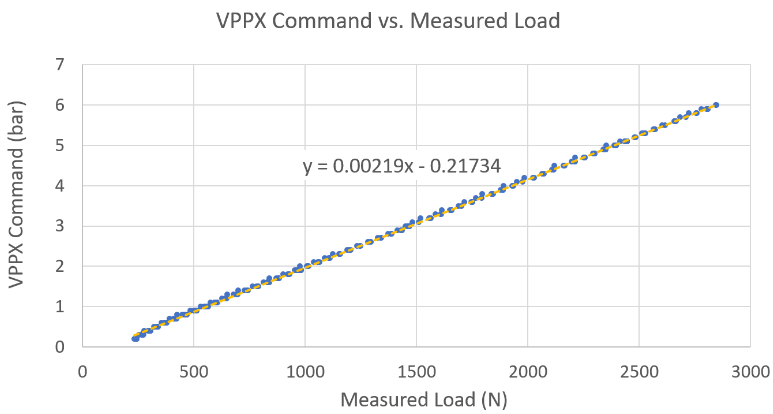


Figure 4.17: VPPX Command vs. Measured Load.

From the obtained data (Figure 4.17), we are able to extrapolate a linear relation between these parameters:

$$VPPX\,Command\,(bar) = 0.00219 \times Measured\,Load\,(N) - 0.21734 \tag{4.1}$$

This equation (4.1) is then used to command the VPPX as a function of the desired load, taking into account the load offset configured during the "Positioning" state:

$$VPPX\ W+ = 0.00219 \times (Desired\ Force + Load\ Cell\ Offset) - 0.21734 \qquad (4.2)$$

When changing the regulated pressure value, the VPPX valves do not respond instantaneously to their command, this results in a natural ramp of load application on the specimen without the need to implement such load application ramp via software. And so, the first time the while loop runs the VPPX valves are closed but all the following cycles during the "Test in Progress" they will be internally regulating their pressure, aiming for a setpoint value that was obtained through Equation 4.2, gently rising from 0 bar to that value in the first few seconds of the test.

A test can end in one of three distinct forms: the user can end it by pressing the button on the display, the available course limit can be reached or the specimen can rupture. This last two events are monitored automatically by the software and all three do not need to wait for the next "saving moment" to occur. They can happen as fast as the computer can run the while loop, which happens every few milliseconds.

The course limit is monitored using the lower travel limit switch. If actuated, it is detected that the available course was exhausted and the test is finished via software. Its important to recall that, the electric circuit will also detain the directional valve from allowing airflow into the upper chamber of the cylinder if the travel limit is actuated.

If the specimen ruptures, we will continue to have pressure in the upper chamber, but no longer have a tensile force on the specimen as a result of this pressure (the load cell will still measure some load because of the weight of the upper assembly). We already have a relation between the VPPX command and the measured load (Equation 4.1) and the VPPX did a fairly good job at controlling its output pressure when this relation was being obtained. So, we will use it to implement a crude specimen rupture detection procedure.

We will say that, after the initial ramp of load application, if the the measured load is below 60 % of the expected load for the pressure measured in the VPPX, the connection between the lower and upper assemblies must have been severed and so the specimen has ruptured. Even being as simple as is, this detection method was tested and during all trials has never misfired of failed to detect a specimen rupture.

Once one of the three test ending events happens, a new line of text is appended to the saved data file. It contains the date and time and the reason why the test ended (in Figure 4.18 we can see an example of the save file generated during a test which was ended by the user). Besides this, a message is displayed to the user, informing him that the test has ended, and the reason why it ended (Figure 4.19). As soon as the user acknowledges the message by pressing the "OK" button, the station moves on to the "Test Finished" state.

```
New Test        25-Jul-18       16:57
Elapsed Time (s)        Measured Load (N)       Desired Load (N)        Position (mm)
0.000   -0.207  200.000 -0.028
3.104   180.895 200.000 -1.237
6.149   186.490 200.000 -1.470
9.198   190.220 200.000 -1.637
...
3723.235        201.617 200.000 -16.244
3726.270        202.135 200.000 -16.234
3729.305        201.720 200.000 -16.253
Test Finished by User
```

Figure 4.18: An example of the saved file (truncated).

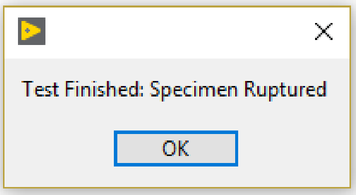


Figure 4.19: A "Test Finished" message.

4.11 State: Test Finished

In this state, the station's panel displays a message informing the user that the test has ended, the resulting data has been saved and asks him to remove the specimen from the station (Figure 4.20).

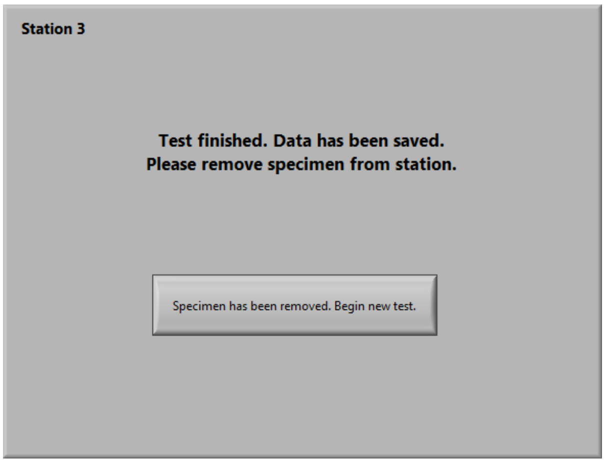


Figure 4.20: "Test Finished" GUI.

Once the user clicks the button, confirming the removal of the specimen from the station and wanting to start a new test, the program checks that the DADE is still referenced. If it is not, the station moves on to the "Referencing" state. If the DADE still has its reference, the directional valve is actuated to allow airflow to the upper chamber and the VPPX set to 4 bar. Once the lower travel limit switch is reached, both valves are reset and the station moves on to the "Test Parameters" state, ready to begin a new test.

4.12 State: Emergency

This state is programmed differently from the remaining states. Although most of its code also runs inside the main case structure, the event itself is triggered outside of this. Whatever the active case may be, if an emergency is detected, this case value overrides whatever the value the shift register would take.

If one of the emergency buttons is pressed, the directional valve is disengaged (forcing it to return to its closed position) and the pressure regulator valve closed. The *PC EMERG* variable is set to "true", also triggering the *PC EMER* relay, redundantly disengaging the directional valves and the machine enters emergency mode.

A message appears on screen warning of the emergency stop and allowing the user to go to an emergency state where the valves can be controlled via the computer (Figure 4.21).

The user can only go to the emergency controls once the physical emergency button is disengaged. If the user clicks the "Go to Emergency Controls" button and the emergency button is still actuated the warning just flashes again, not leaving the screen and the controls remain locked.

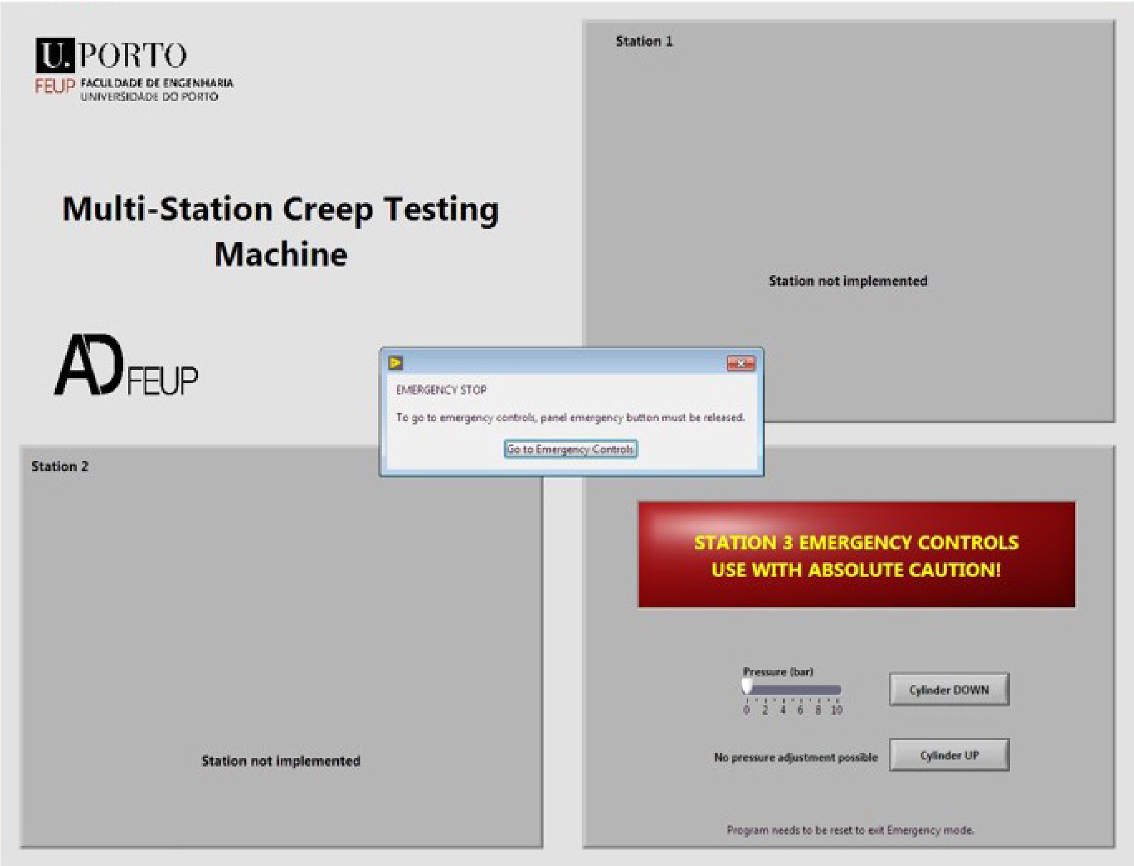


Figure 4.21: Emergency Stop warning.

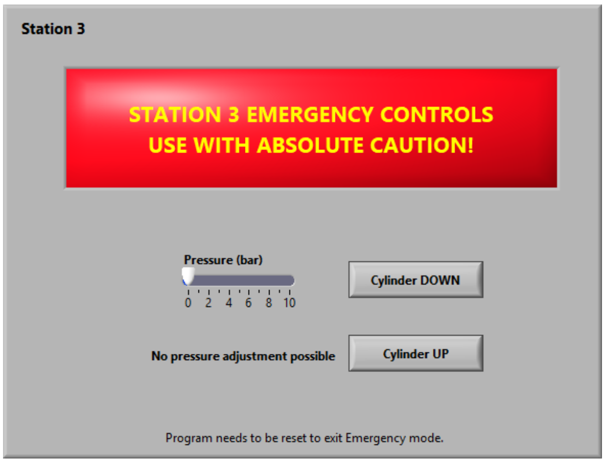


Figure 4.22: Emergency Controls.

The Emergency Controls panel allows the user to regulate the VPPX pressure, and to move the cylinder up or down (Figure 4.22). This can be useful if, for example, something is stuck in the station. Above the controls, a display warning a cautioned use of these emergency controls keeps flashing red. The programming behind this state (Figure 4.23) couldn't be more simple as we just have the controls directly associated with the variables used by the DAQ assistants, a case structure disengaging the *PC EMER* relay (to allow for the valves' actuation) and the blinking of the warning display.

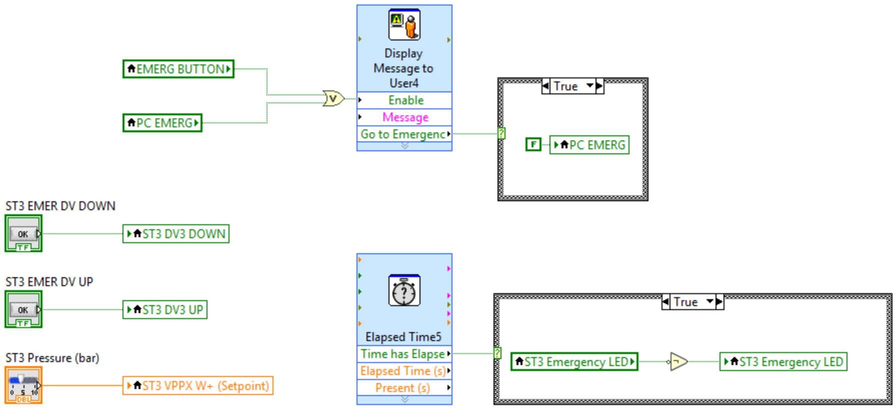


Figure 4.23: Emergency Controls block diagram.

To leave the emergency mode, the program must be reset. This was intentionally programmed to prevent an accidental exit of this state.

4.13 Discussion

The machine is commanded and supervised by a computer. The software, programmed in LabVIEW, works independently for the three stations and is, for now, only implemented for Station 3, although the easy implementation of the remaining two stations was kept in mind during the software development.

Each station has eight possible states, each associated with a different display to the user. The machine starts waiting to commence the necessary referencing of the encoders (we are using relative encoders). Once the user allows it, the machine conduces this procedure automatically. After that, the test parameters are introduced, followed by the specimen assembly in the station. The machine then realizes the creep test, while periodically saving the pertinent data. Once the test ends, be it because the specimen ruptured, because the available course was exhausted, or because the user decided to end the test, the machine awaits for the specimen removal and, after that, is ready to start a new test.

The emergency state is triggered independently from the other states. Once triggered, the directional valves are closed, blocking airflow into and out of the cylinders' chambers. Once the emergency button is manually disengaged, the user can go to a post emergency state, were the controls of the station are unlocked and made available.

Chapter 5

Test Results

In this chapter several tests performed after the machine completion are presented and analysed.

5.1 Endurance Test

With the machine fully assembled and the command software software implemented, some tests were performed to verify that the machine's behaviour was the expected and to validate the machine's capabilities. Figure 5.1 shows the machine during a creep test.

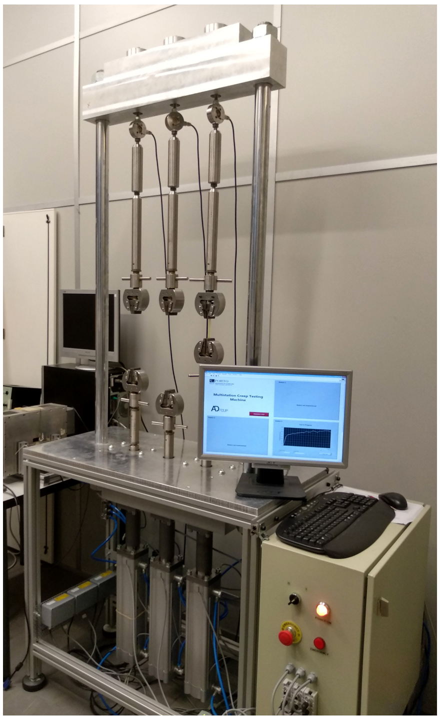


Figure 5.1: The Creep Test Machine performing a test.

One of the main concerns was related with the machine's ability to exert a certain amount of force during long periods of time.

As we are using a fixed reference value for the VPPX valves' pressure regulation (as explained in Section 4.10), one feared that, over time, eventual existing friction forces would be overcome and, consequently, the machine would increase its testing load. In opposition, the machine could, for unknown reasons, reduce its testing force over time - although this last hypothesis seemed less likely because of the way the load on the specimen is regulated.

To test this, the machine was put into functioning for several hours while recording the measured load. The machine was put into action aiming for a desired load of 2000 N, with a specimen of insignificant deformation under this loading conditions, and left running alone overnight with a sample rate of 5 samples/minute.

After 16 h 9 min the test was stopped. As can be seen in Figure 5.2, the machine was able to hold its load for the entire duration of the test, disproving the concerns presented in the previous paragraphs.

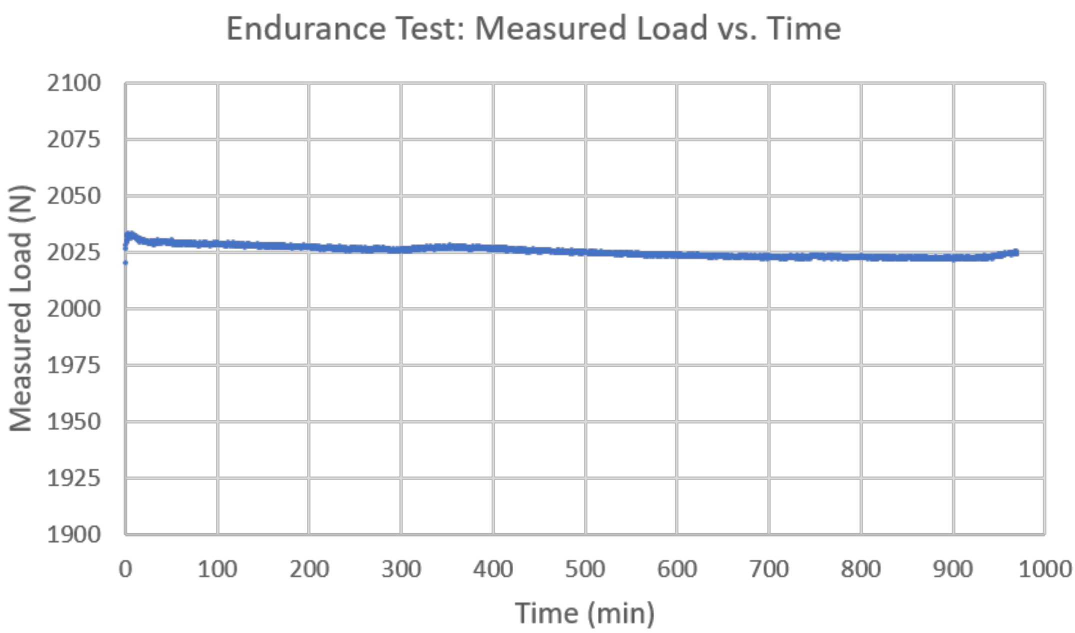


Figure 5.2: Endurance Test: Measured Load vs. Time.

In the following analysis, lets ignore the first 30 s of the test, because of the load application ramp mentioned in Section 4.10. As Table 5.1 shows, the average load was slightly above the desired load with its variation on the specimen ranging from +1.1 % to +1.7 %. This can be a result of using a linear approximation of experimental data for the command of the VPPX valves. The equation may be slightly higher than the proper adjustment value for this range of forces which, for now, is not a big concern since the offset is so small.

Although being higher than it should be, the load varies very little during the course of the test: after the load application ramp, the minimum value was 2021.6 N and the maximum 2033.5 N, which means that the envelope of variation is under 12 N in a test with a desired force of 2000 N. This is a very good result, showing that the VPPX valves performance is even better than expected.

Table 5.1: Endurance test results

Desired Load	2000 N
Average Load	2025.4 N
Standard Deviation	2.32
Min. Load Deviation	+1.1%
Max. Load Deviation	+1.7%
Load Variation Envelope	11.9 N
Total running time	16h 9min

5.2 Adhesive Creep Tests

To show that the machine is able to hold a certain force over long periods of time is not enough to prove that it works properly. The best approach to show this is to compare results with independent testing.

At the time of writing, ADFEUP was starting creep research using the two component epoxy paste adhesive Araldite AW 106/Hardener HV 953 U. This adhesive is advertised as a multi-purpose adhesive with a long working life and so, to study its behaviour regarding a phenomenon were time dependence is the chief characteristic is specially pertinent [37].

Two bulk specimens were kindly prepared by the ADFEUP researcher in charge of the project who also supervised the testing (in Figure 5.3, Specimen 1 can be seen (after its test) alongside Specimen 2 (before its test)). A third specimen was also made available to test using this machine. This specimen was however already damaged on one of the strapping ends, making harder its fixation to the machine. Besides the defect in Specimen 3, the specimens were of equal geometry.

The tests were stopped, by the ADFEUP's researcher indication, not long into the secondary creep phase because, for this particular adhesive, this phase is very long and the researcher was not particularly interested in the forthcoming data. Specimen 3 (orange line) was the exception. Because of the mentioned damage to one of the strapping ends,

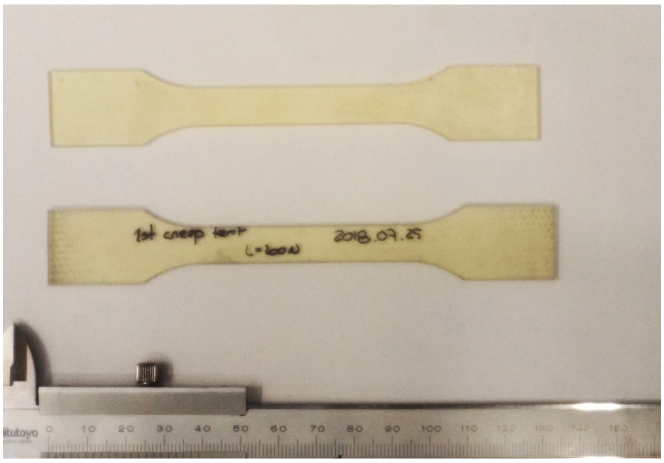


Figure 5.3: Bulk adhesive specimens (top: untested; bottom: after creep test).

the specimen slipped from the station's jaws before the machine being ordered to end the test. The tests results are presented in Figure 5.4.

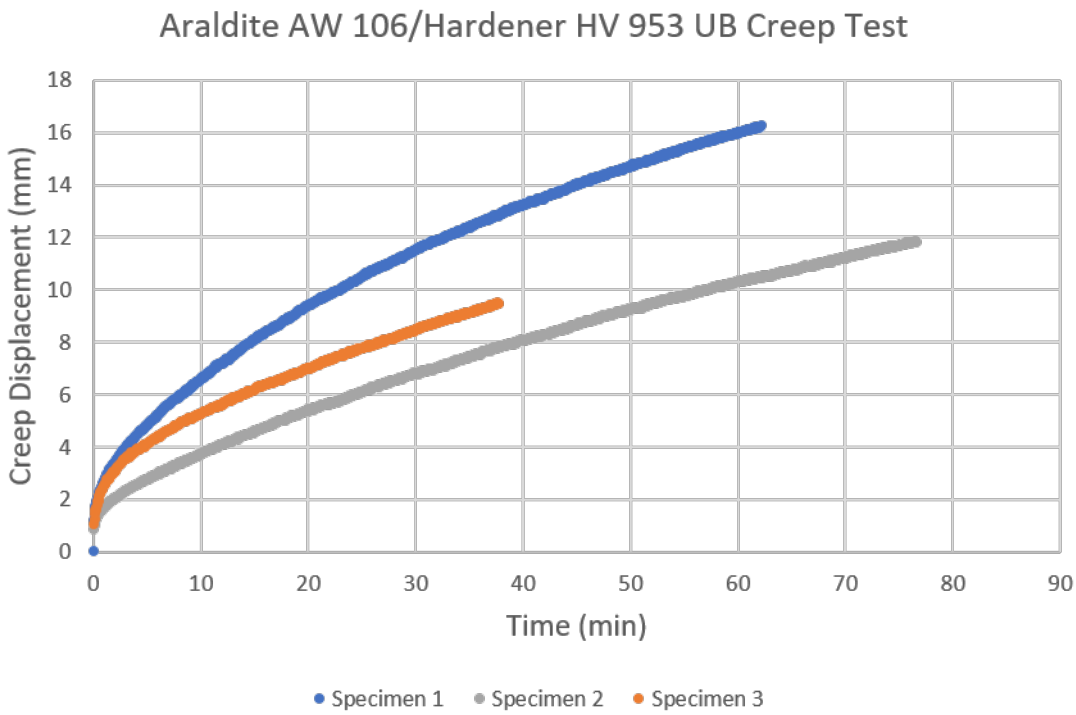


Figure 5.4: Araldite AW 106/Hardener HV 953 U creep test.

Unfortunately, at the time of writing, ADFEUP still didn't have more results involving this adhesive. Besides that, the three tests were made at uncontrolled temperatures.

The variation between the three results can be explained easily: the temperature in the laboratory can vary more than 10 °C during the day, the tests were made at different times of day and this particular adhesive is very temperature sensitive.

Although the creep data from these tests cannot be used to validate the machine's capabilities, we can still use the remaining data to further analyse the performance of the machine regarding its load imposing capabilities.

Table 5.2: Araldite AW 106/Hardener HV 953 U test results

	Specimen 1	Specimen 2	Specimen 3
Desired Load	200 N	200 N	200 N
Average Load	201.7 N	201.3 N	199.6 N
Standard Deviation	1.32	1.66	1.11
Min. Load Deviation	−2.5 %	−3.4 %	−2.6 %
Max. Load Deviation	+2.2 %	+1.9 %	+0.9 %
Load Variation Envelope	9.3 N	10.7 N	6.8 N
Total running time	62 min 9 s	76 min 37 s	37 min 47 s

As we can see in Table 5.2, the average loads are very similar to the desired loads. Unlike the test aiming for 2000 N, the variation on these new tests is centred right on target, at around 200 N. This tells us that the command equation is properly adjusted around this range of forces. The standard deviation for the measured loads in these tests is also lower than on the endurance test. The force variation envelope still appears to be around 10 N, which hints that this may be the valves' limit in their ability to control the pressure, and still remains a perfectly acceptable load variation.

5.3 Lead Specimens Tests

ADFEUP has recently taken possession of a WP 600 experimental unit (Figure 5.5). This apparatus, manufactured by GUNT, is destined for educational and demonstration purposes involving creep.

Although the machine is very limited and, because of that, ADFEUP cannot use it for its creep studies, it came with a set of lead (Pb) specimens which would be used to demonstrate the creep phenomena. In addition to the specimens, the machine also came with creep data of tests performed using similar specimens. We shall use some of these specimens (Figure 5.6) to perform creep tests using our machine and compare the resulting data with GUNT's.

On Figure 5.7 we have the resulting data from our five tests overlapping GUNT's graphs. GUNT provided three creep curves (blue lines): a test performed under a tension stress of 12.5 N/mm^2, one at 12.0 N/mm^2 and one at 11.0 N/mm^2. As all the used

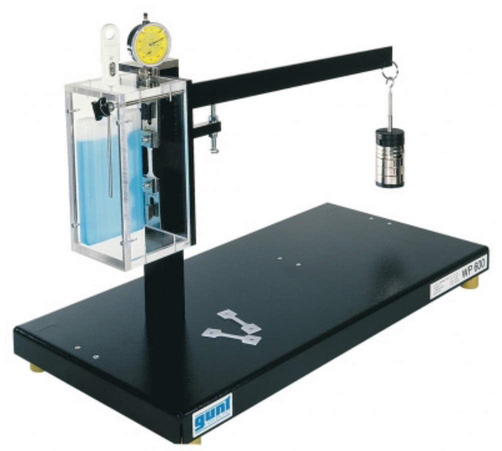


Figure 5.5: WP 600 experimental unit [38].

Figure 5.6: A lead specimen after testing.

specimens were of equal geometry, with a section area of $10\,\text{mm}^2$, we get that, with our specimens, the blue lines would represent tests at 125 N, 120 N and 110 N.

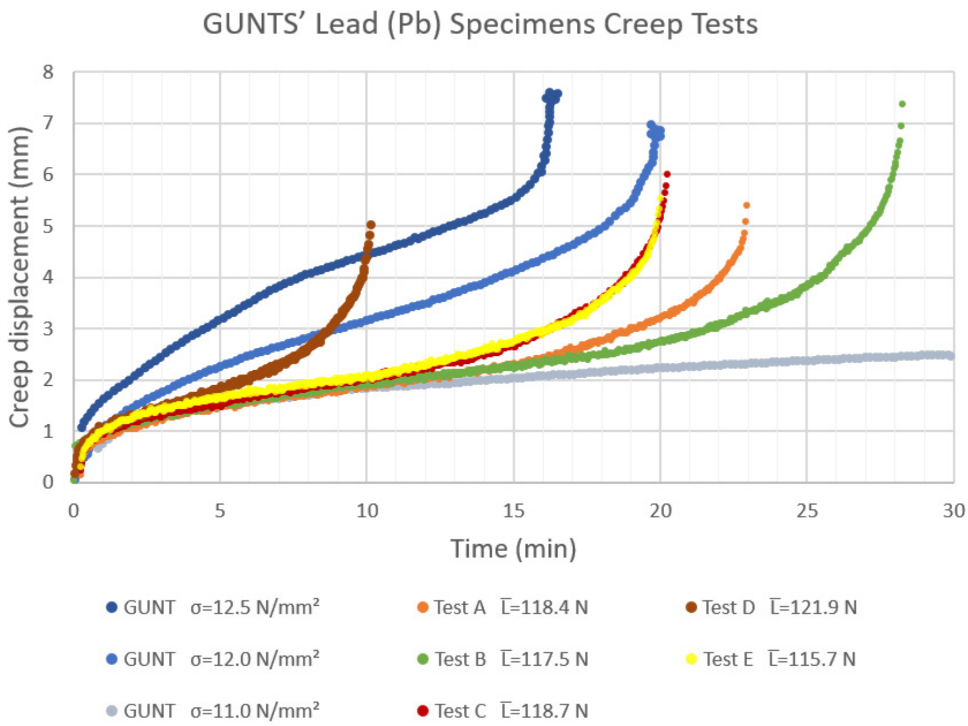


Figure 5.7: GUNTS' Lead (Pb) Specimens Creep tests.

Test A (orange line) and Test B (green line) aimed for a desired load of 125 N, however for both tests the average load ($\bar{L}$) was lower than this value, reaching 118.4 N for Test A and 117.5 N for Test B. For Test C, the desired load was adjusted slightly higher, to 130 N, but still, the average load for this test was just 118.7 N. Considering the average load of each of this tests, instead of the desired load, the results are very promising. All show creep deformation consistent with the data provided by GUNT, all of them falling between the 11.0 N/mm^2 and the 12.0 N/mm^2 curves, in the right order. This gives us confidence that both the load measurements and the displacement measurements are accurate.

Test D aimed for a 135 N load, also falling short with an average load of 121.9 N. On Test E, we returned to the desired load of 130 N value, obtaining again a lower average load of 115.7 N. The creep results for this two tests however are not as expected. Both specimens suffered a greater deformation than what was to be anticipated. The most likely scenario is that this abnormal results are due, not to a flaw in the system measurements but, to a specimen section area inferior to the one considered. Although this difference in the specimens' section was not noticed before the tests, it should be noted that if the specimen's area was of 9.5 mm^2 instead of the considered 10 mm^2, a test performed at an average load of 121.9 N would result in a tension stress of 12.8 N/mm^2, resulting in a much faster creep than the upper reference given by GUNT. It is curious that Test E resulted in a curve almost perfectly identical to the Test C results. Assuming that Specimen C had a perfect area of 10 mm^2, the area of Specimen E would need only to be of 9.7 mm^2. This differences in the specimens' areas are very possible, and could even have been caused when handling the specimens as they are extremely ductile, bending just under their own weight.

As already said, all tests had an average load under the desired load. As Table 5.3 shows, the five tests have negative deviations from the desired load. This tells us that, despite being well adjusted for values around 200 N, the command equation for the VPPX valves is under the proper adjustment value for this range of desired loads. It is important to notice that these forces are near the lower limit of the machine's capabilities.

Table 5.3: GUNTS' lead (Pb) specimens tests results
(Des. Load = Desired Load, Av. Load = Average Load, St. Dev. = Standard Deviation, Min. Dev. = Min. Load Deviation, Max. Dev. = Max. Load Deviation, L. Var. Env.= Load Variation Envelope)

	Test A	Test B	Test C	Test D	Test E
Des. Load	125 N	125 N	130 N	135 N	130 N
Av. Load	118.4 N	117.5 N	118.7 N	121.9 N	115.7 N
St. Dev.	1.47	1.35	1.32	1.38	1.20
Min. Dev.	−10.1 %	−14.3 %	−11 %	−12.0 %	−13.6 %
Max. Dev.	−2.9 %	−5.0 %	−6.8 %	−8.1 %	−9.1 %
L. Var. Env.	9.0 N	11.7 N	5.5 N	5.2 N	5.9 N
Total Time	22 min 44 s	28 min 14 s	20 min 1 s	10 min 8 s	19 min 47 s

Although the deviations seem much bigger in these tests than in the previous ones it also should be noted that the load variation envelope remains at around 10 N - even being considerably smaller for three of them - and that 10 N is 8 % of 125 N, what explains why the deviations in percentage seem so high for these tests when compared to the previous ones.

5.4 Discussion

The machine has proven to be able to hold loads for large periods of time whilst saving the pertinent data.

The command equation for the VPPX valves appears to be well adjusted for load values around 200 N, but slightly higher than the desired value for tests near the upper load testing limit of the machine, and lower than the desired value for tests near the lower testing limit of the machine. Although these deviations are not very serious, further experimental data should be collected and the equation for the VPPX valves command adjusted based on this data. Even if it requires the collection of more data, the adjustment of the command equation would be easy to implement on the machine's software and would improve its performance.

The machine seems to be able to control loads within an envelope of approximately 10 N.

Creep tests using lead specimens from GUNT seem to confirm the machine's accuracy in the recorded displacements and load measurements.

Chapter 6

Conclusions and Future Developments

This chapter comprises the main conclusions of the dissertation, reporting the achieved objectives and addressing the possible future improvements to the machine.

6.1 Conclusions

The machine's mechanical components, designed in previous dissertations were assembled. An extension rod, correcting an overlooked flaw of the machine was designed, manufactured and integrated into the machine. The proposed pneumatic circuit was analysed and improved, the missing components were chosen and ordered and the circuit assembled. The suggested electric circuit was redefined. The missing components, were defined and acquired or manufactured in FEUP. The circuit has been completely assembled and tested, with the exception of a digital signal conditioning board, which is pending fabrication - this conditioning circuit has been validated using a prototyping board. For this reason, at the time of writing only Station 3 is functional. The pressure regulator valves are working in internal control mode, pending an intervention by the manufacturer.

The machine's software has been defined and programmed from scratch in LabVIEW. Although the software is, for now, only implemented for Station 3, it was developed with the three stations in mind and the implementation for the two remaining stations has been prepared for.

An emergency procedure has been programmed into the machine and redundantly enforced via hardware, minimizing the risks in case of unexpected situations.

The machine can run tests at a constant load between 100 N and 2800 N. It has proven to hold loads for significant periods of time within a load variation envelope of about 10 N. The system enforces automatically the desired load conditions, plots a displacement graph during the test and saves the pertinent data regularly.

The system is able to detect a specimen rupture, ending the test if this occurs, and logging this information on the saved data file. A test can also be finished by the user or automatically, in the case of the station exhausting its available course, in both cases the reason why the test ended is also logged in the saved file.

Tests have been performed, validating the machine's accuracy in measuring loads and the resultant displacements.

6.2 Future Developments

The software, which has proven to function, should be implemented for Stations 1 and 2, and the missing signal conditioning assembled in the electric circuit, completing it.

More experimental tests to validate the machine's abilities should be performed. The proportional valves' commanding equation should be adjusted based on this experimental data while the intervention by Festo to change the VPPX valves' control mode is not performed.

Alterations in the software can be made to allow the machine to perform relaxation tests. Because of the way the software is designed, these alterations are easy to implement: a simple addition to the state machine during the "Test in Progress" state, where, after a certain time or condition, the reference value to the VPPX valves is changed according to a specific user input would be sufficient to allow the machine to perform relaxation tests.

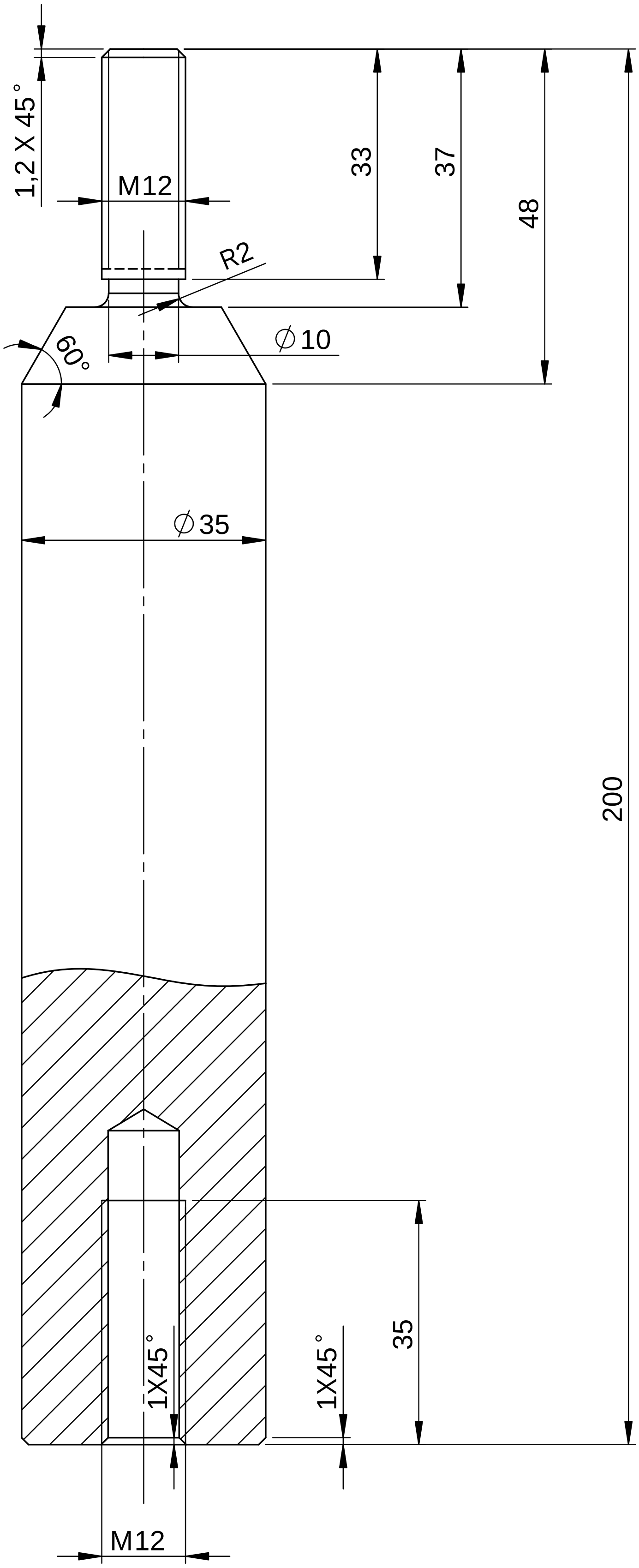
A climatic chamber should be designed and manufactured to allow creep studies at different temperatures.

Appendix A

Technical Drawings

A.1 Upper Coupling Extension

A.2 Valves Support



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Rugosidades Gerais ISO 1302
Cantos e Chanfros ISO 13715

ISO 13920

MATERIAL: AISI 304

	NAME	DATE
DRAWN	Daniel Silva	2018/04/09
CHECKED		
ENG APPR		

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

TITLE: Upper Coupling Extension

A4

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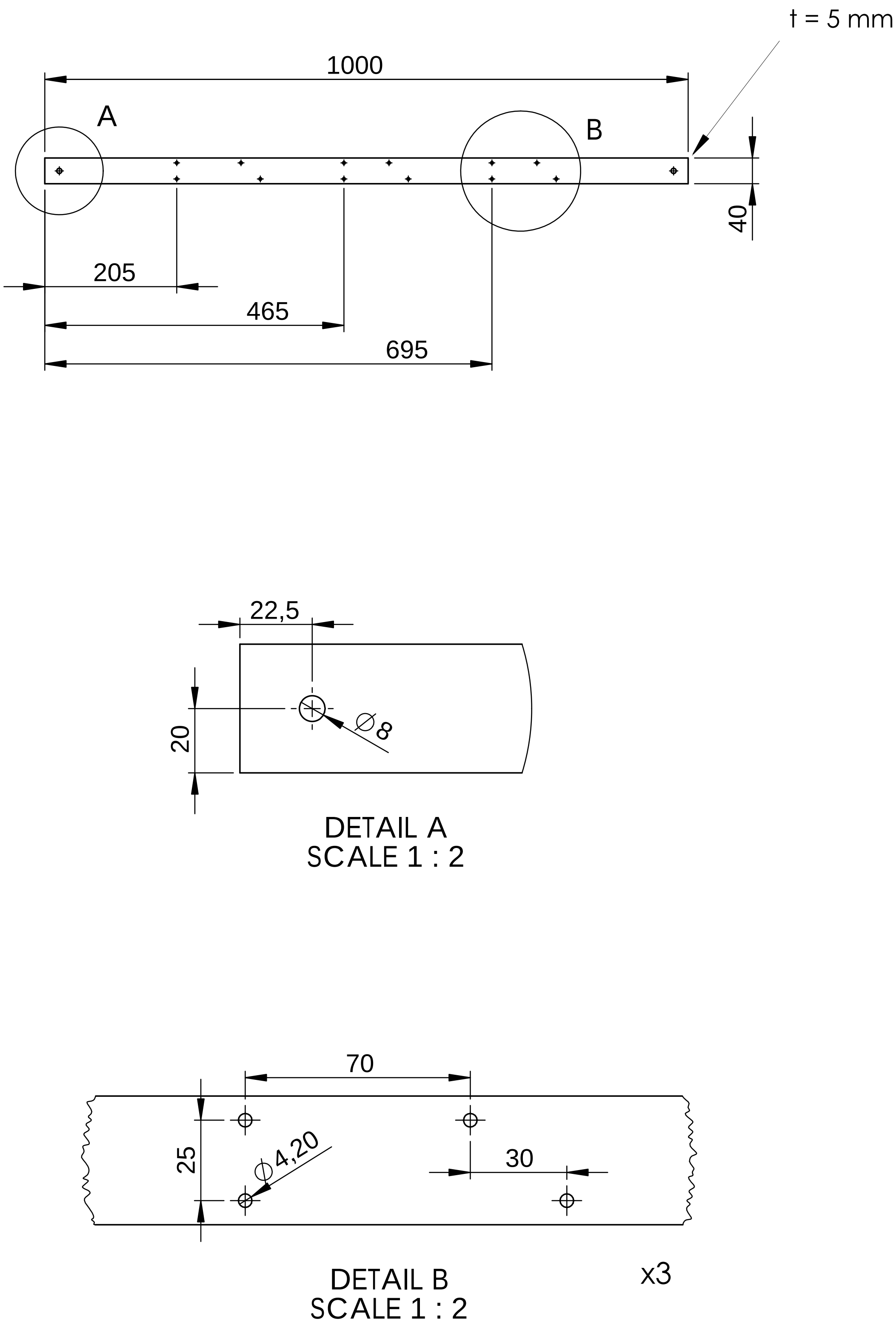
SHEET 1 OF 1



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ISO 13920

MATERIAL:
Aluminium 2014-T6

	NAME	DATE
DRAWN	Daniel Silva	2018/06/05
CHECKED		
ENG APPR		

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

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Valves Support

A4

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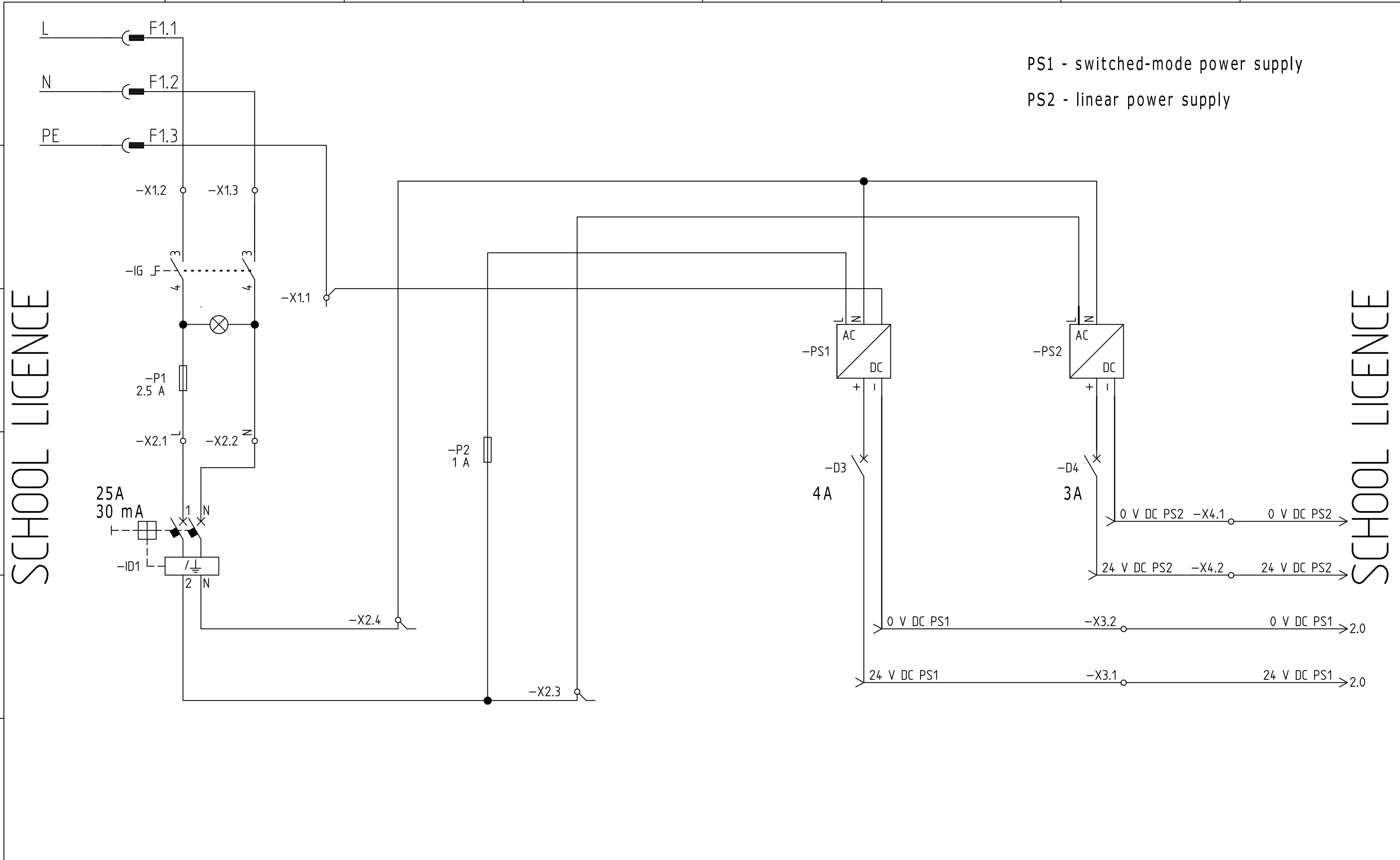
SHEET 1 OF 1

Appendix B

Electric Circuit



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AD FEUP

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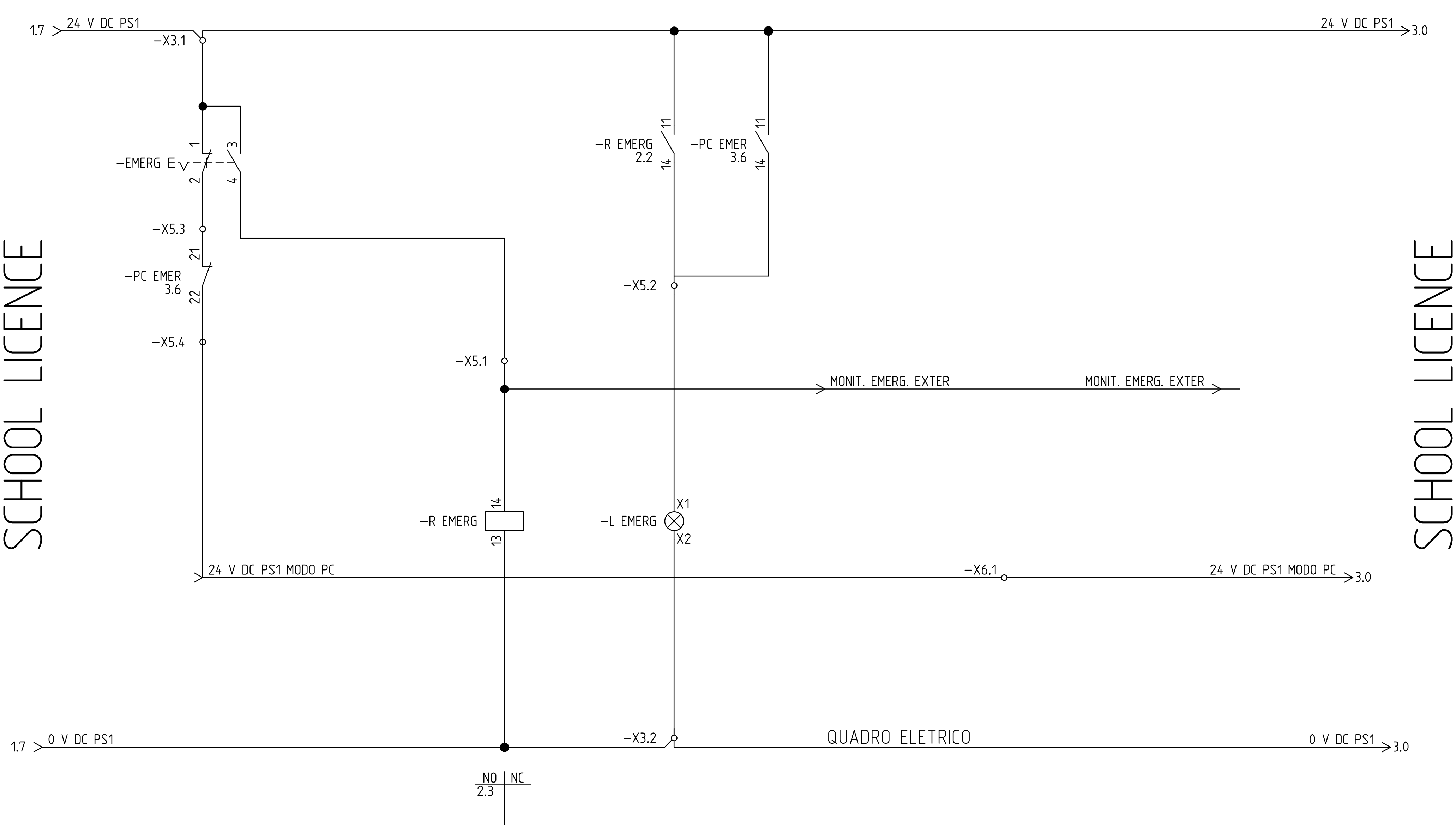

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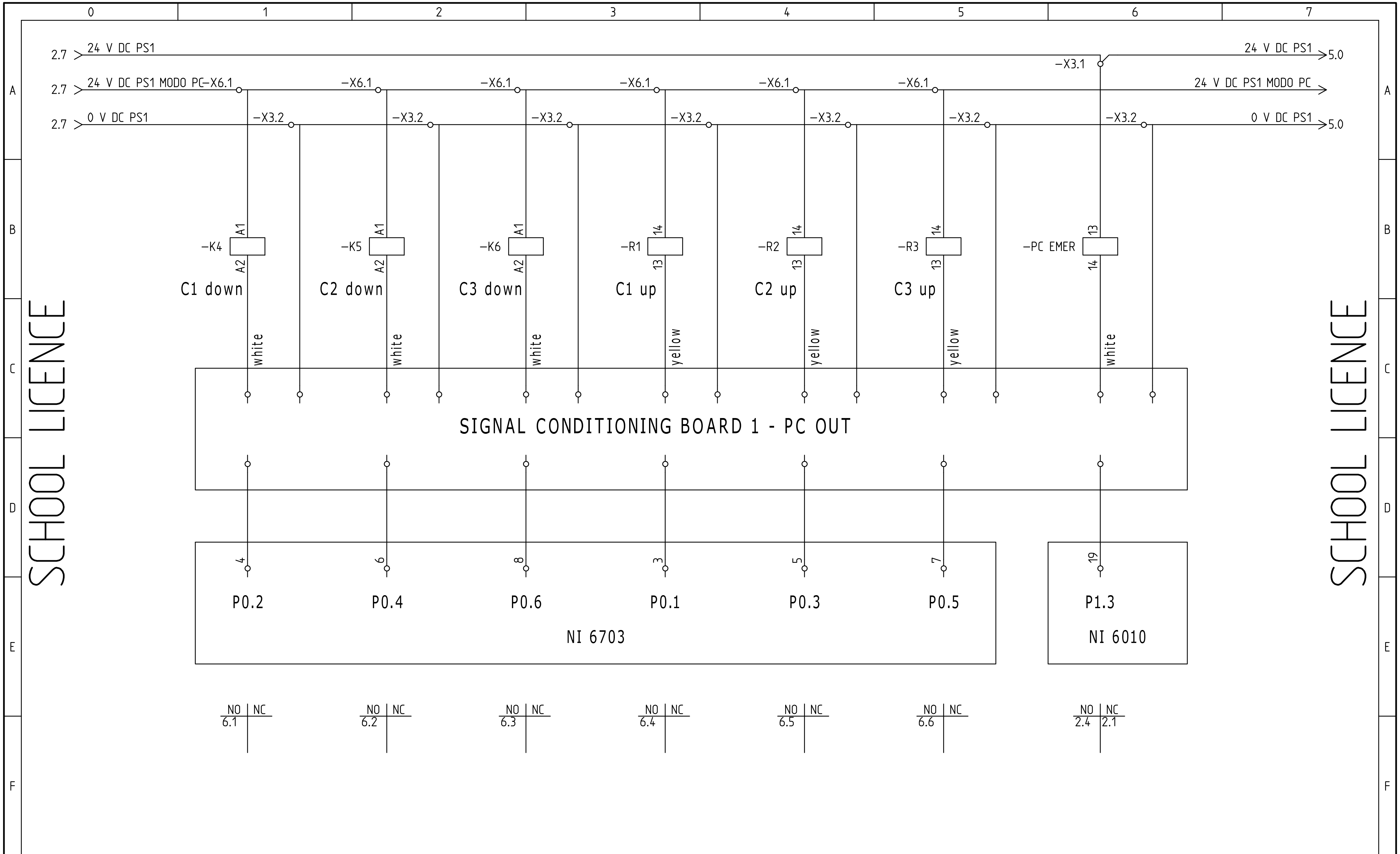

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AD FEUP

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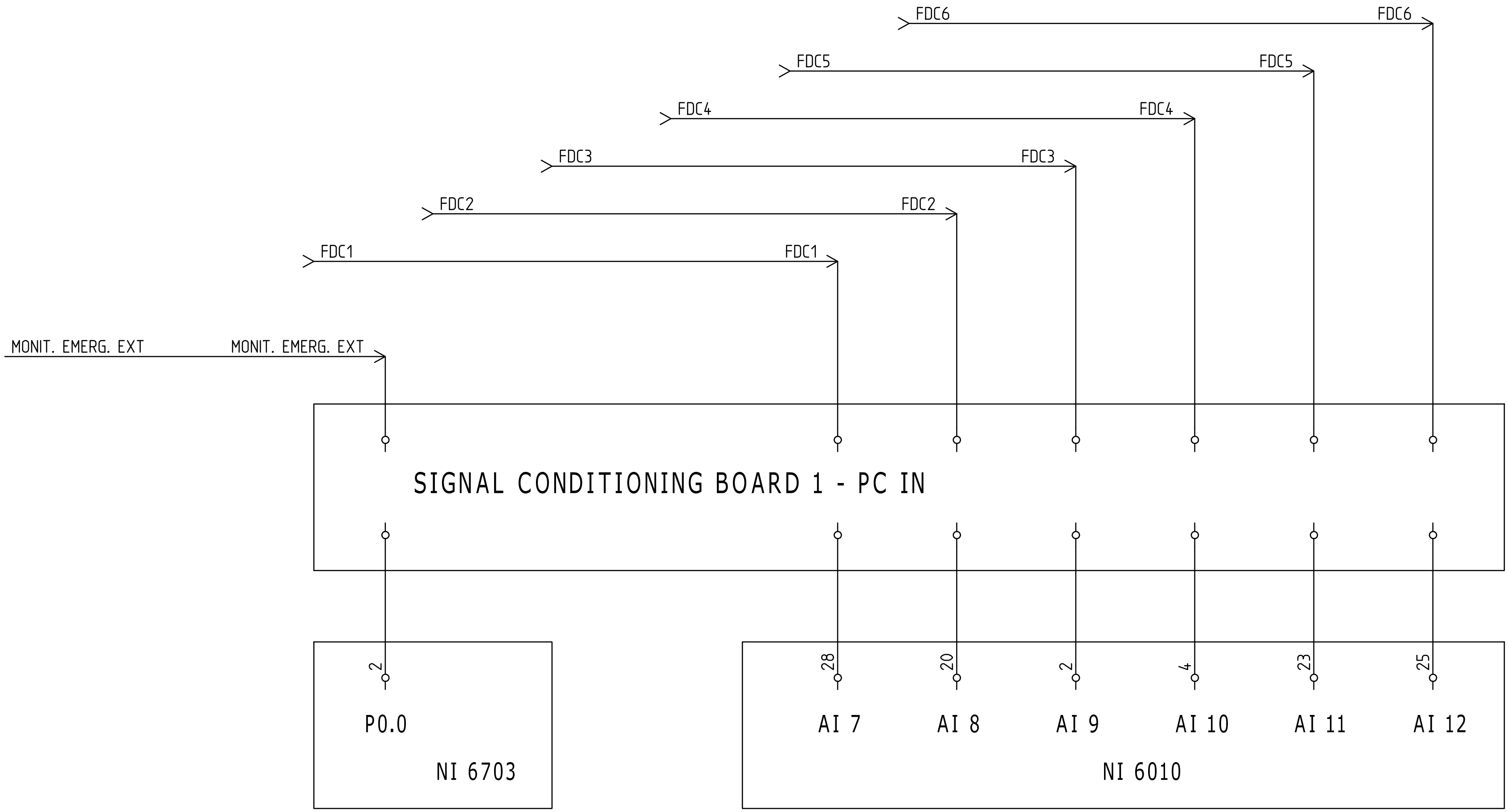

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AD FEUP

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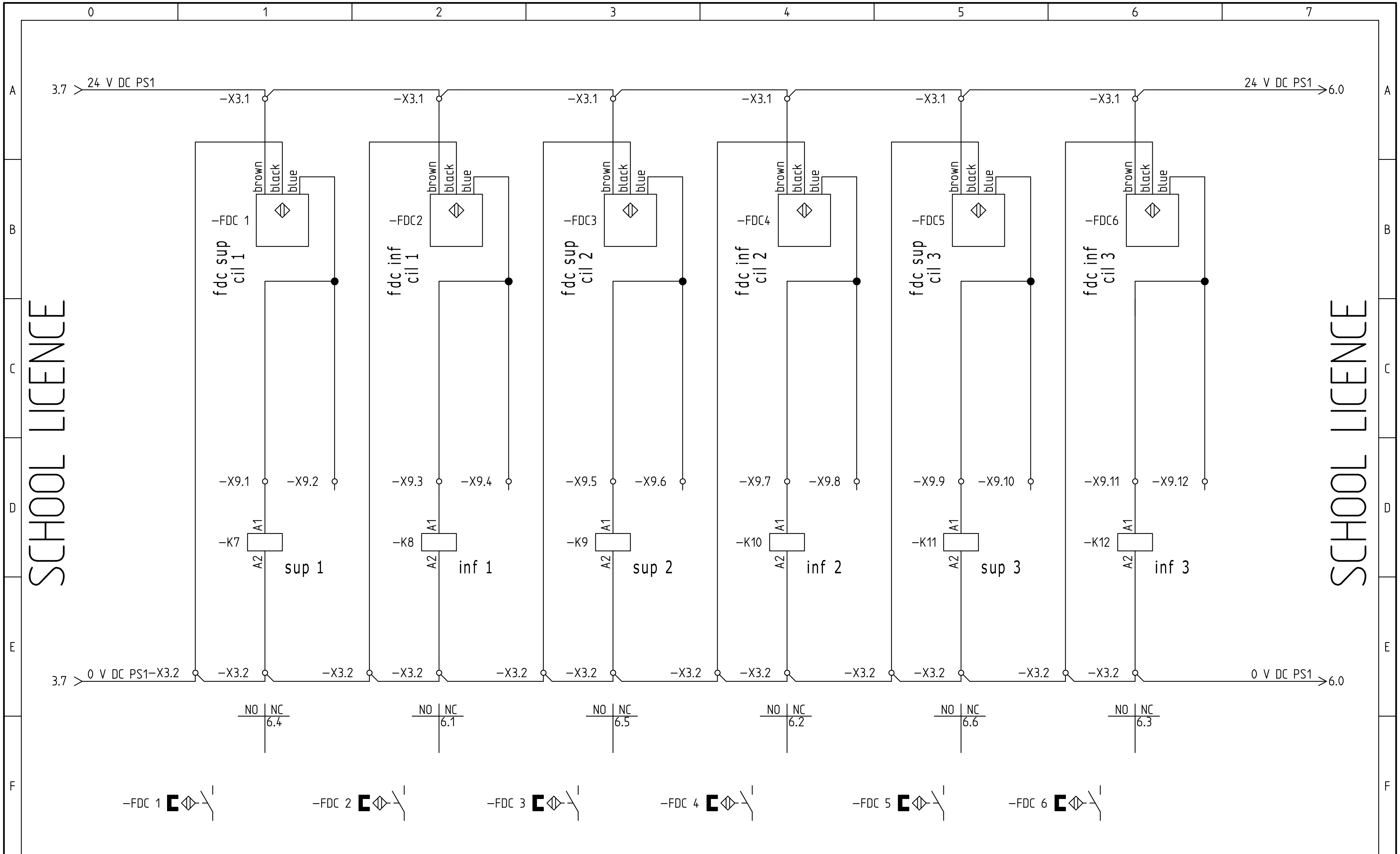

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AD FEUP

TRAVEL LIMIT SWITCHES

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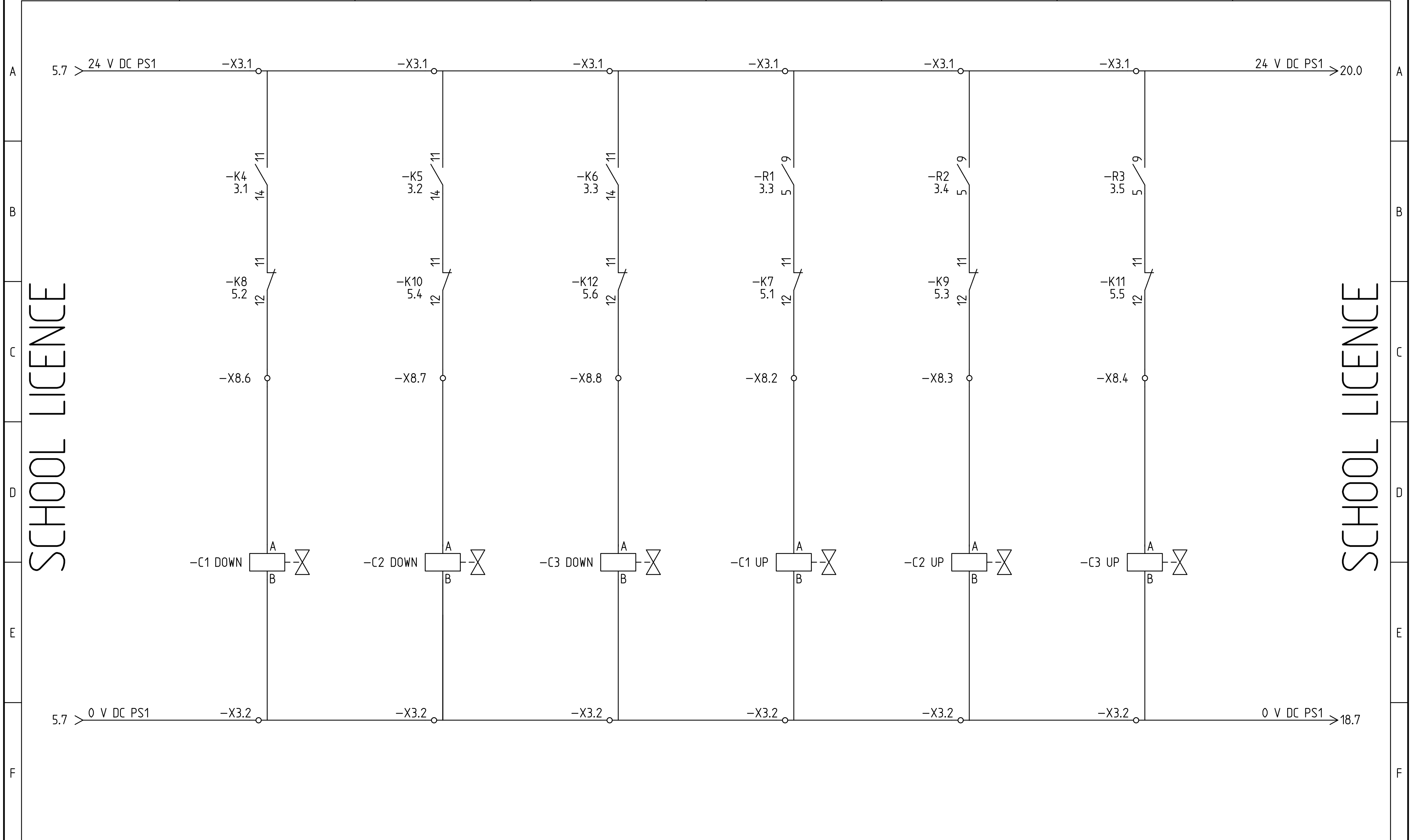

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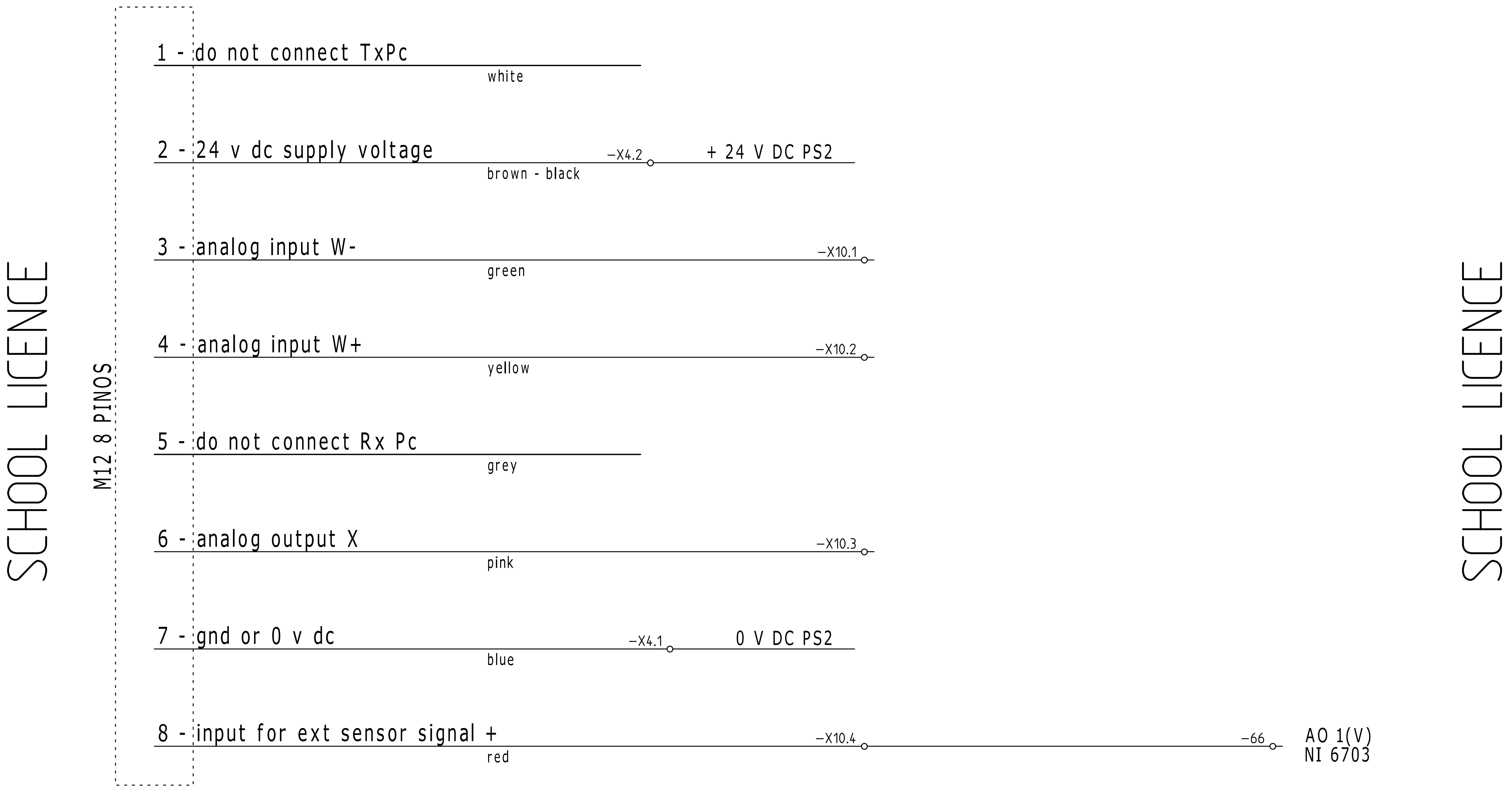

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

VPPX 1

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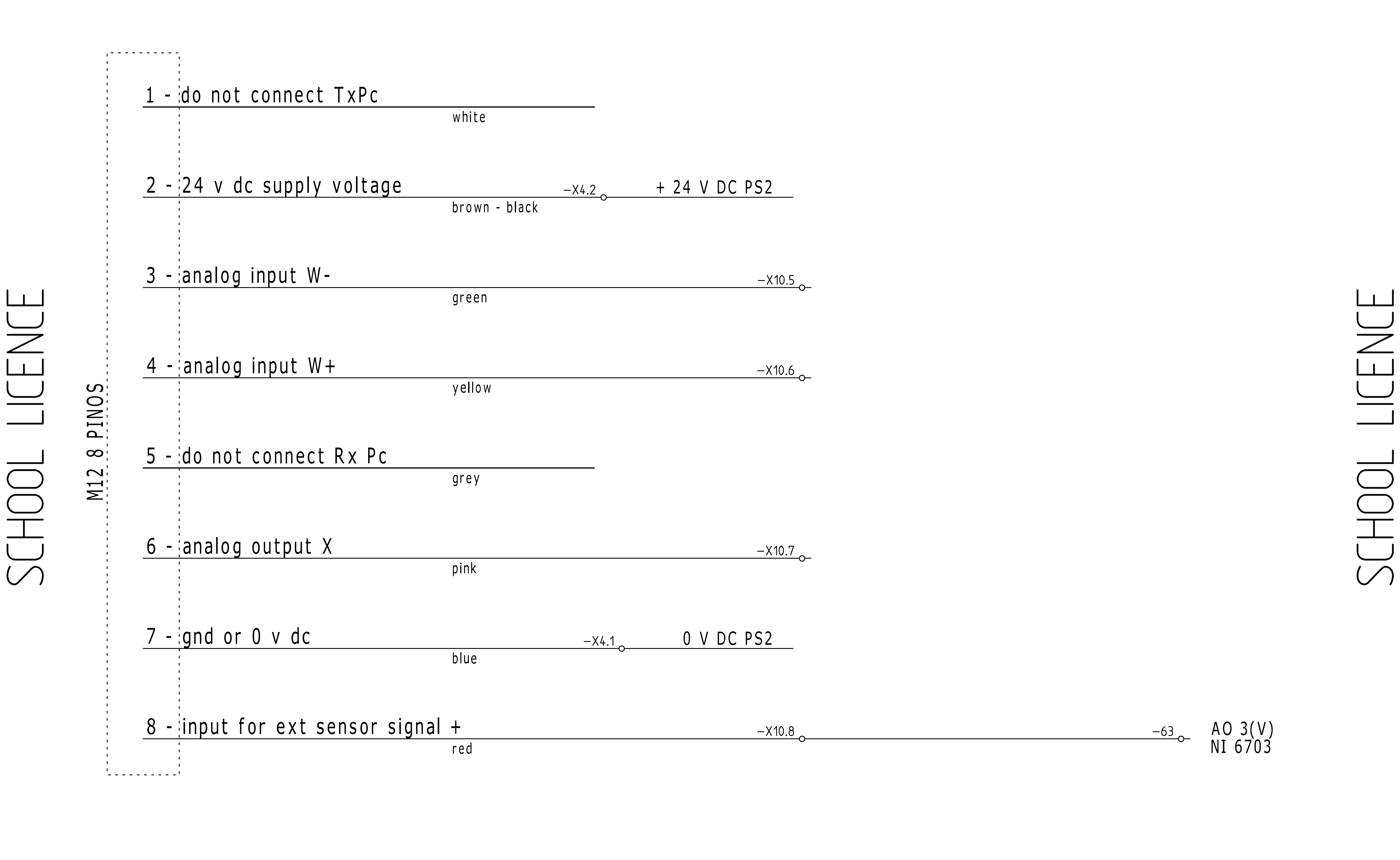

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U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

AD FEUP

VPPX 2

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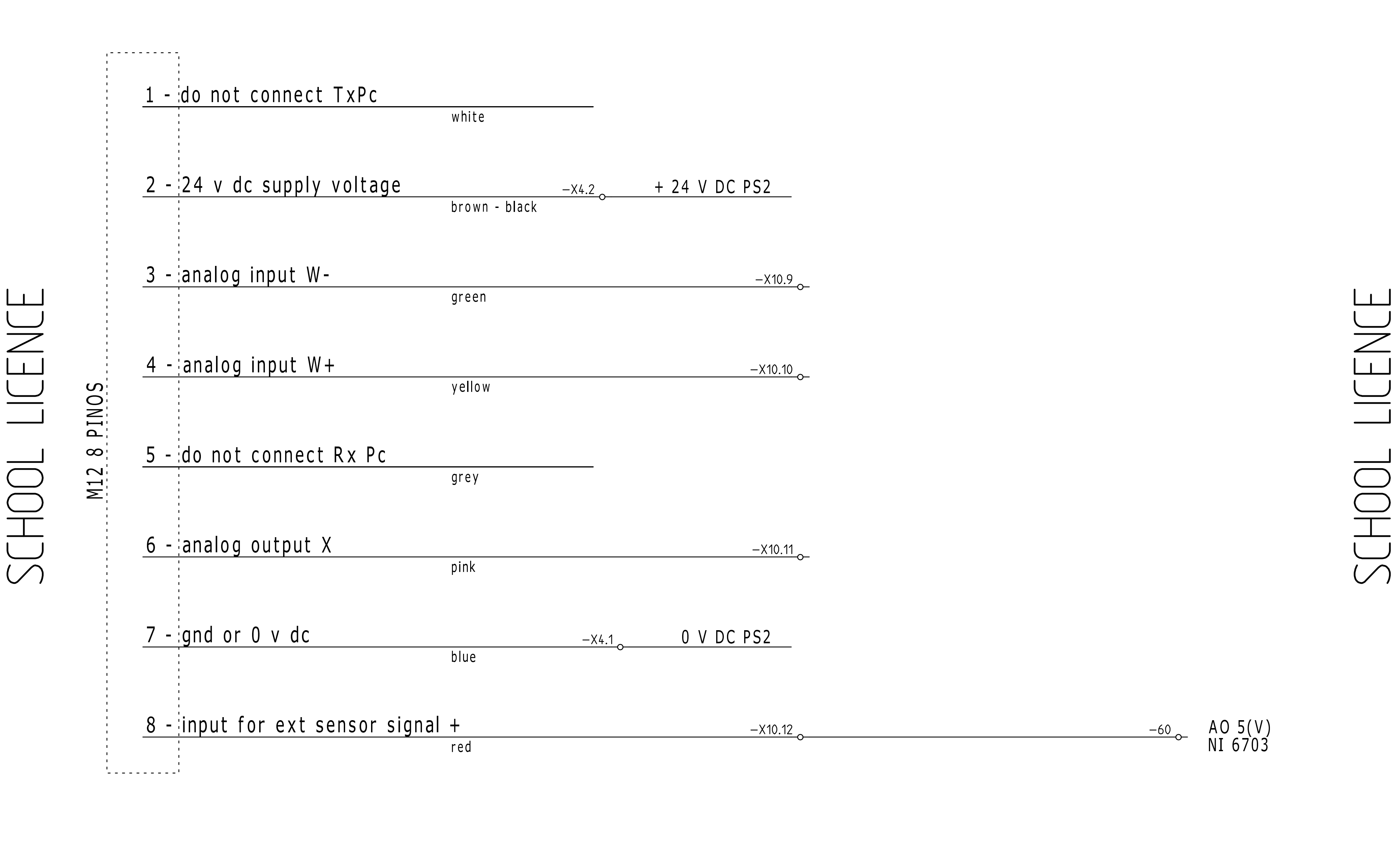

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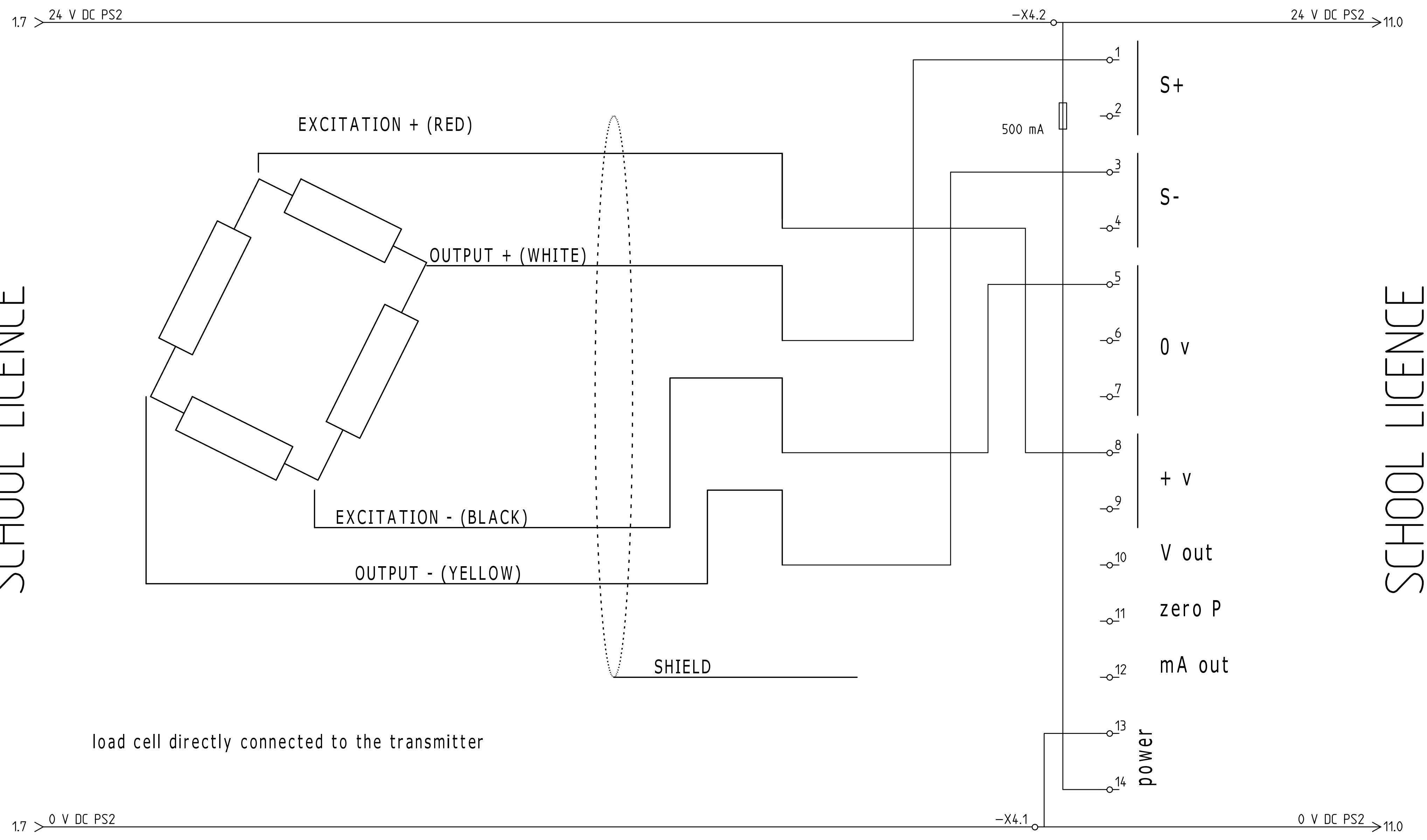

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AD FEUP

1 LOAD CELL TRANSMITTER
PER STATION

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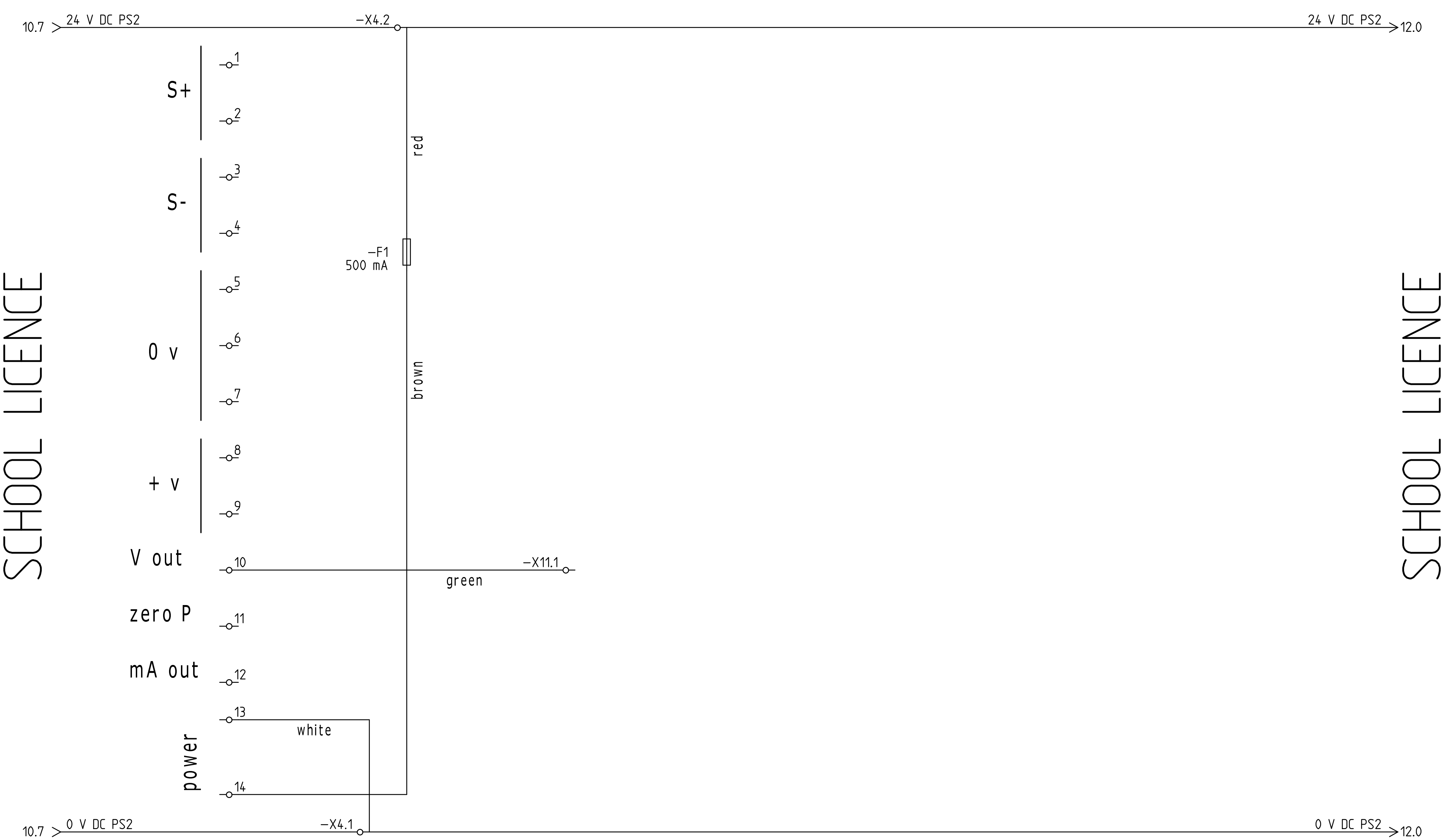

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

LOAD CELL 1 TRANSMITTER

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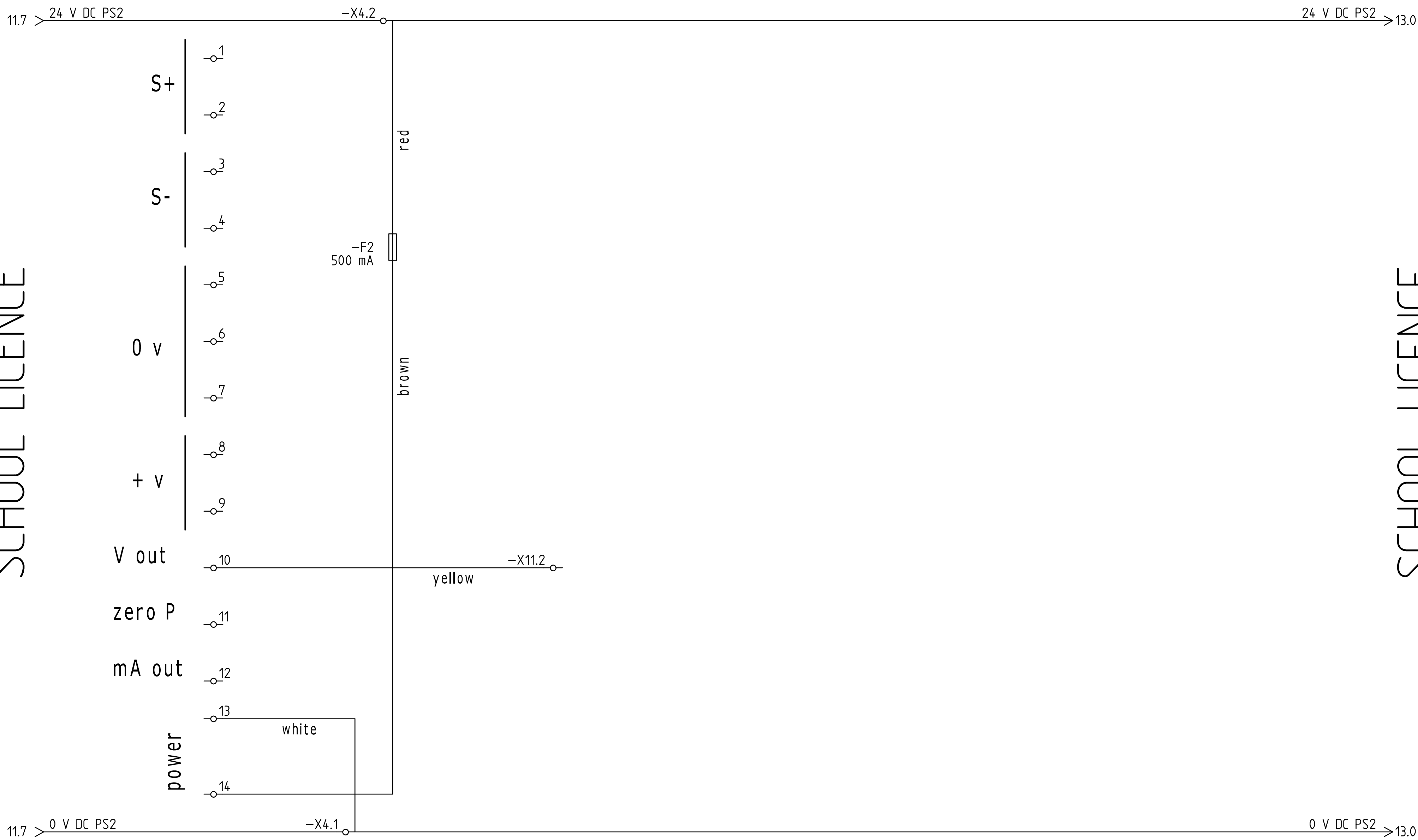
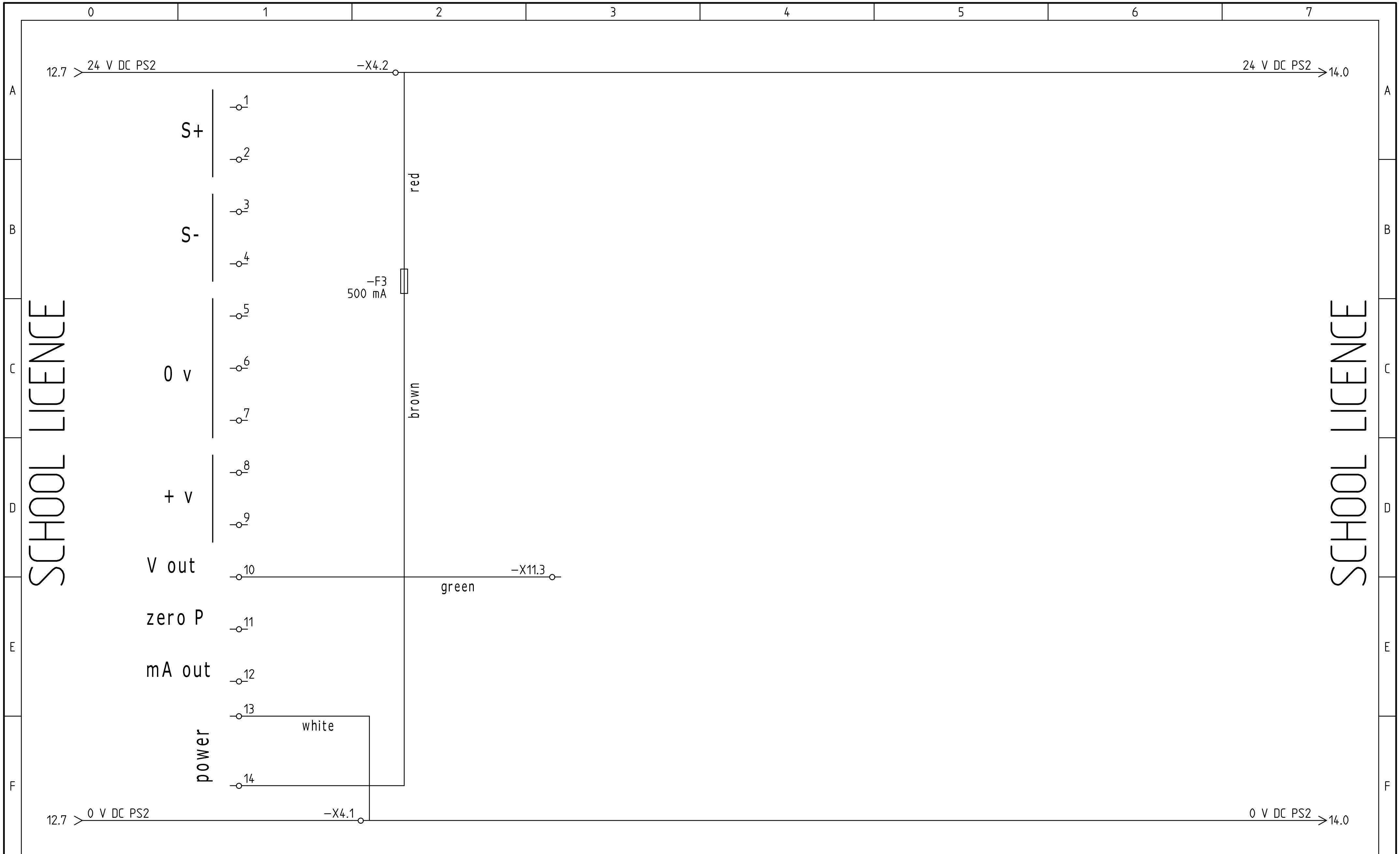


SCHOOL LICENCE

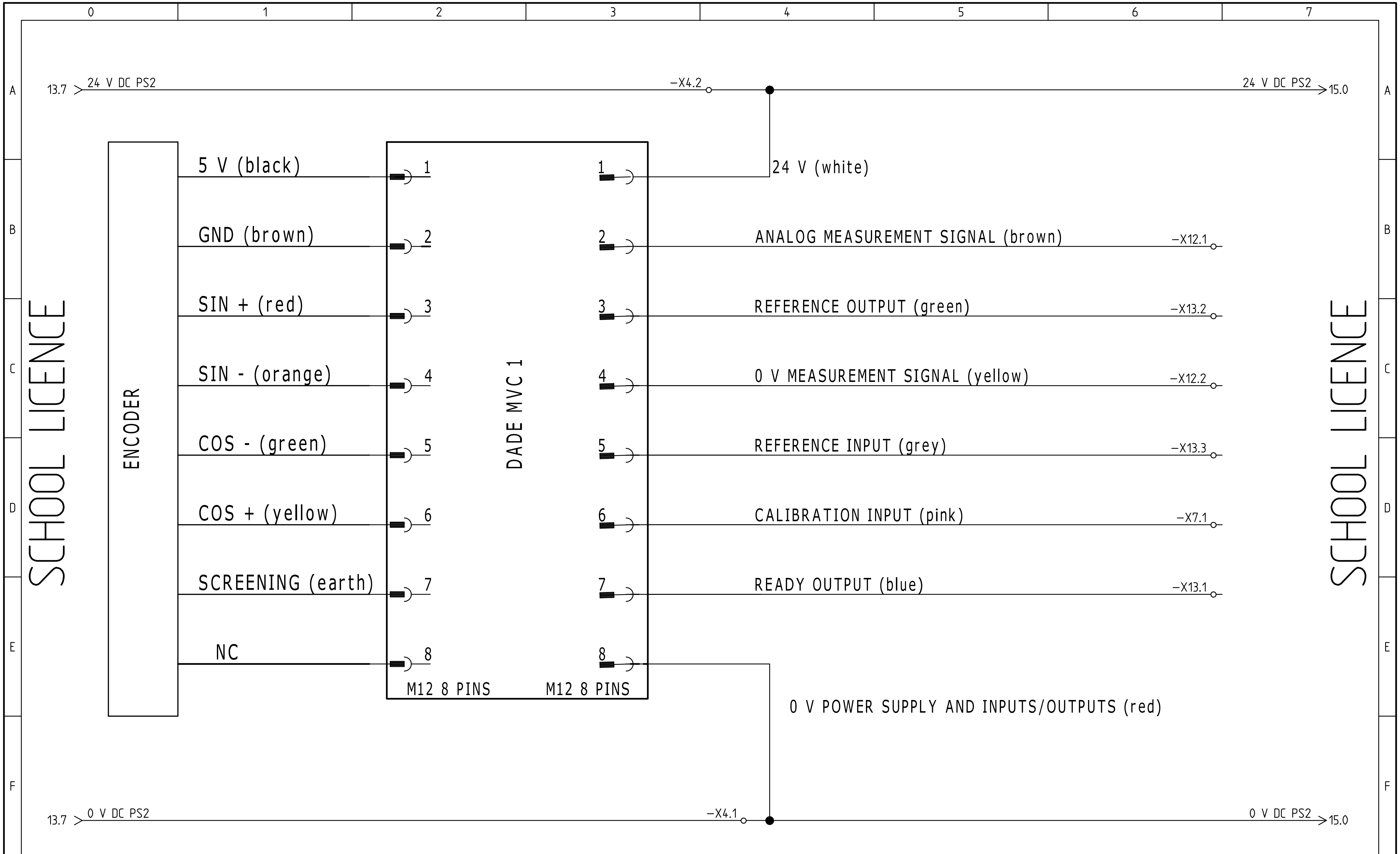
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO	AD FEUP	LOAD CELL 2 TRANSMITTER	Project: Creep	Drawing no.:	Init.:	Rev.:	Sheet: 12
			Date: 21-01-2017	Function:	Location:	Total sheets: 20	Next sheet: 13



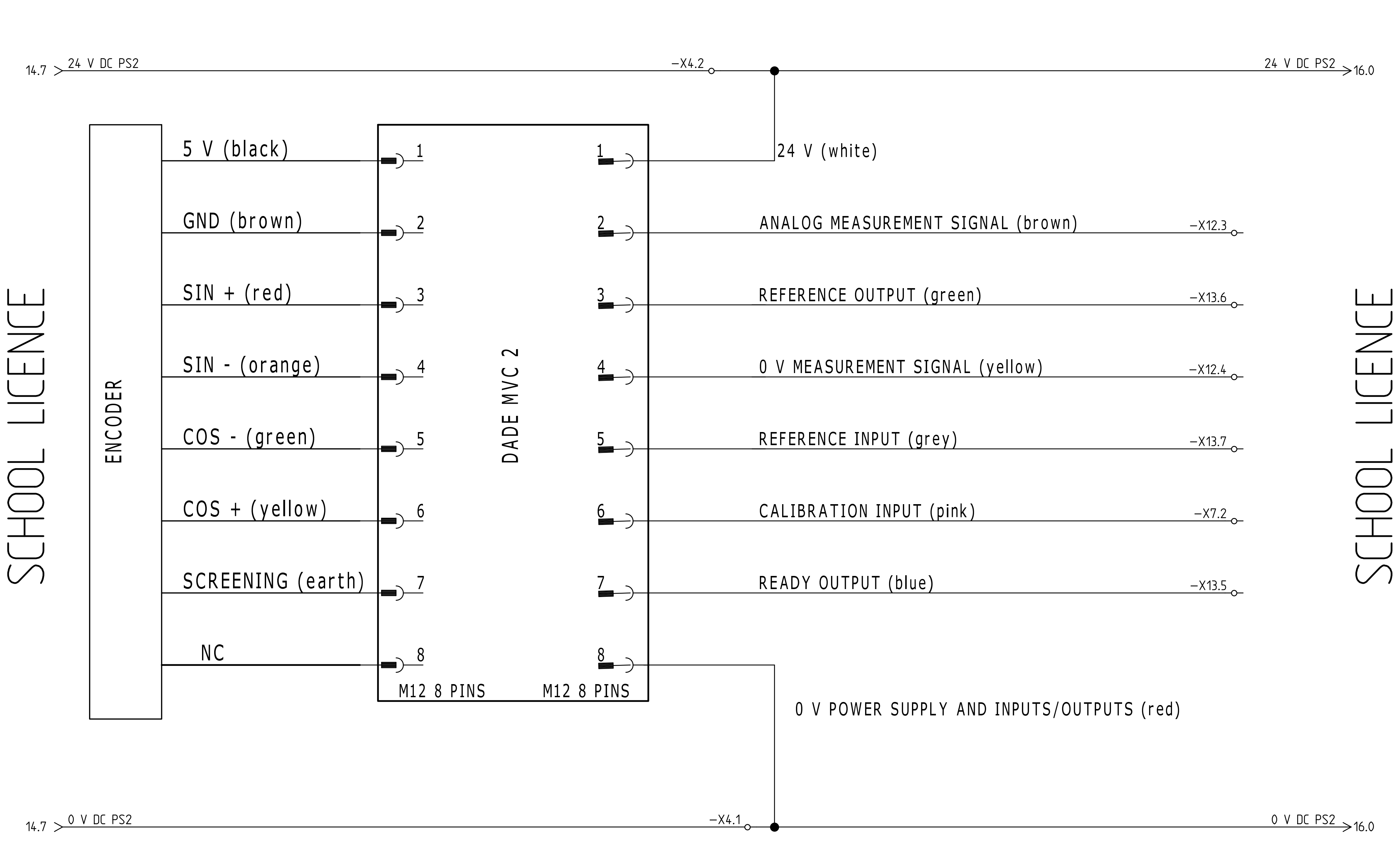
SCHOOL LICENCE

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO	AD FEUP	LOAD CELL 3 TRANSMITTER	Project: Creep	Drawing no.:	Init.:
			Date: 21-01-2017	Function:	Location:

Rev.:		Sheet: 13
Total sheets: 20		Next sheet: 14



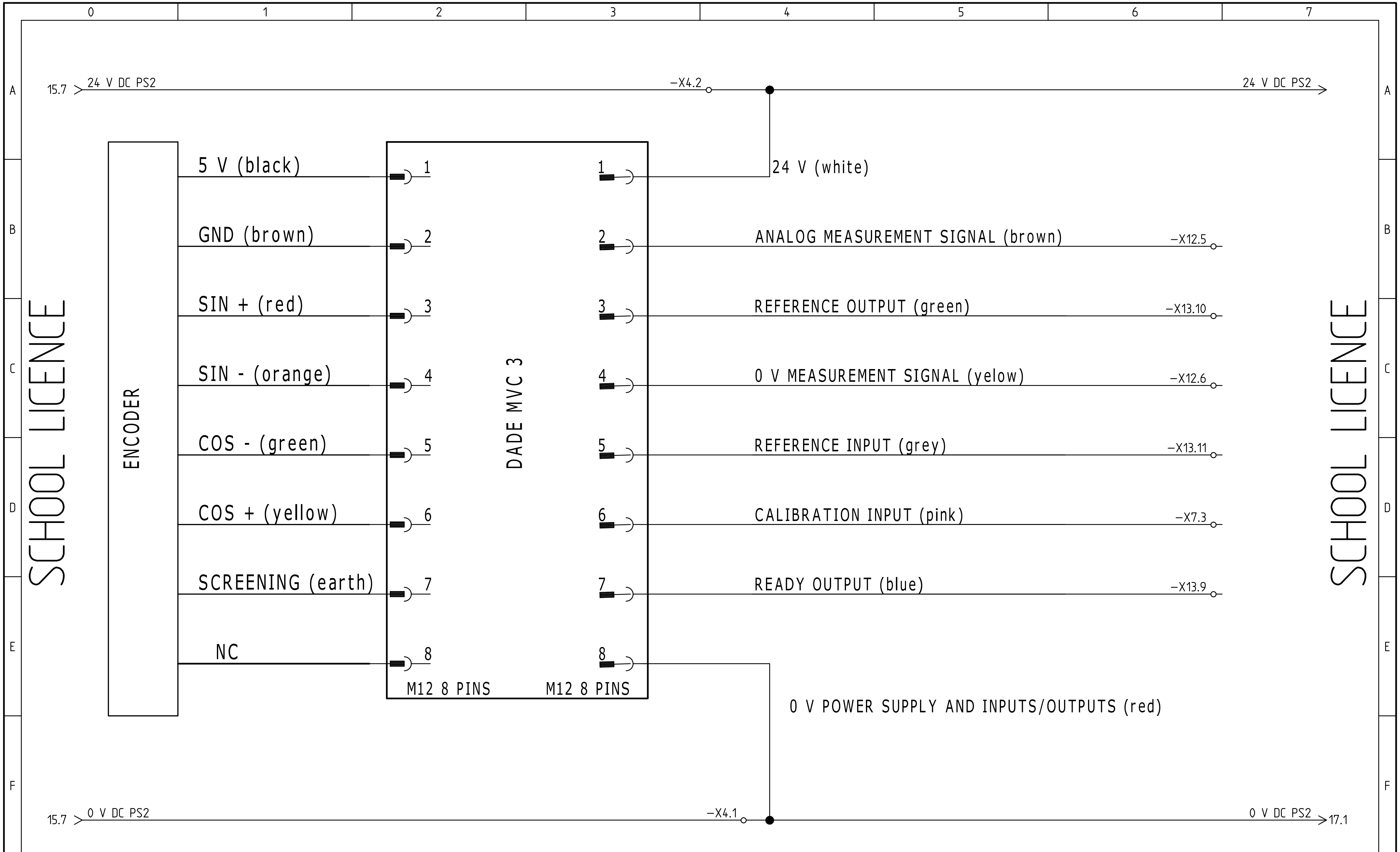
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO	AD FEUP	DADE 1	Project: Creep	Drawing no.:	Init.:	Rev.:	Sheet: 14
			Date: 21-01-2017	Function:	Location:	Total sheets: 20	Next sheet: 15



U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

DADE 2

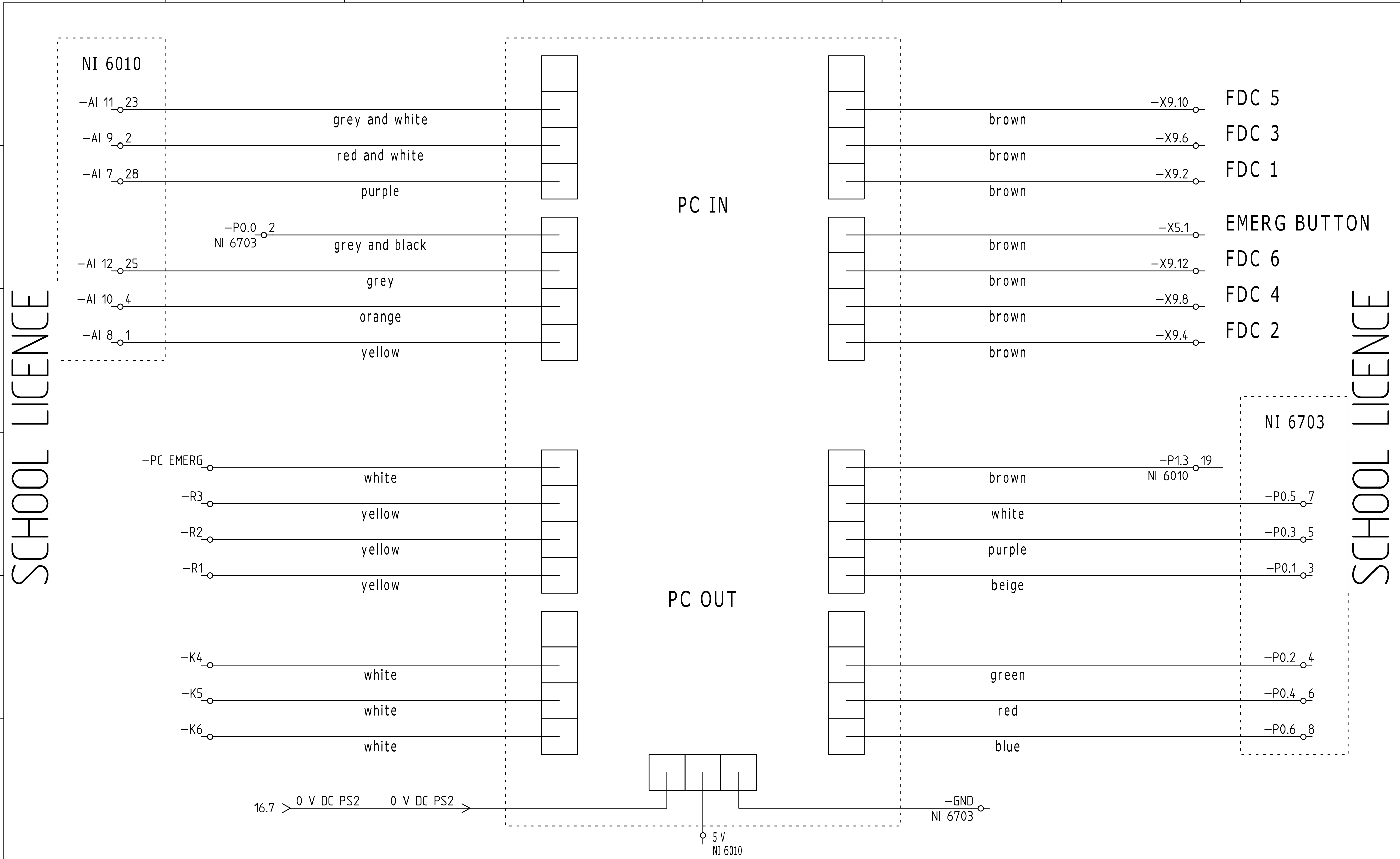
Project: Creep	Drawing no.:		Init.:	Rev.:	Sheet: 15
Date: 21-01-2017	Function:	Location:		Total sheets: 20	Next sheet: 16



U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

AD FEUP

DADE 3	Project: Creep	Drawing no.:	Init.:	Rev.:	Sheet: 16
	Date: 21-01-2017	Function:	Location:	Total sheets: 20	Next sheet: 17



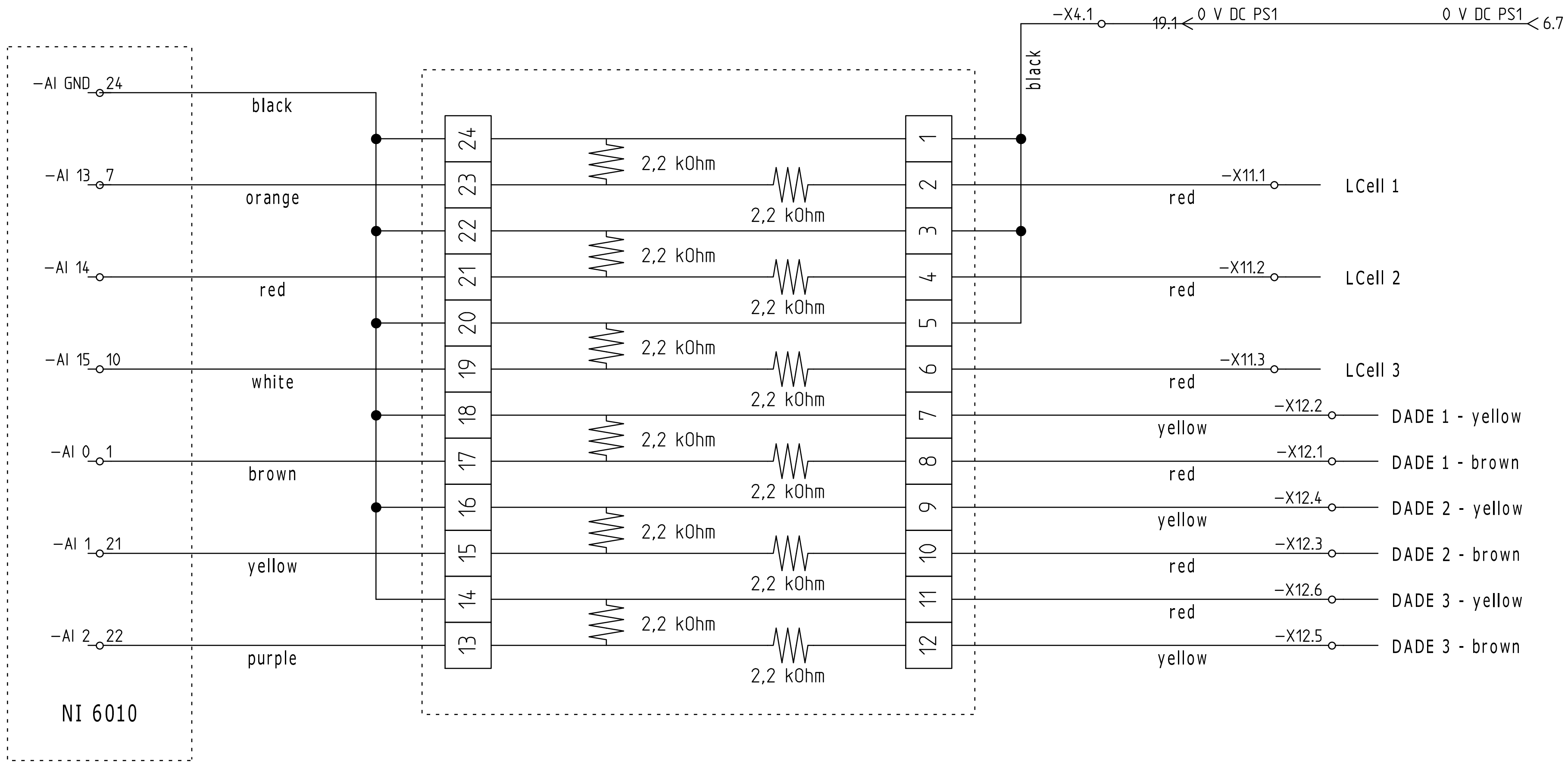
SCHOOL LICENCE

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

AD FEUP

SIGNAL CONDITIONING BOARD 1

Project: Creep	Drawing no.:		Init.:	Rev.:	Sheet: 17
Date: 26/06/2018	Function:	Location:		Total sheets: 20	Next sheet: 18



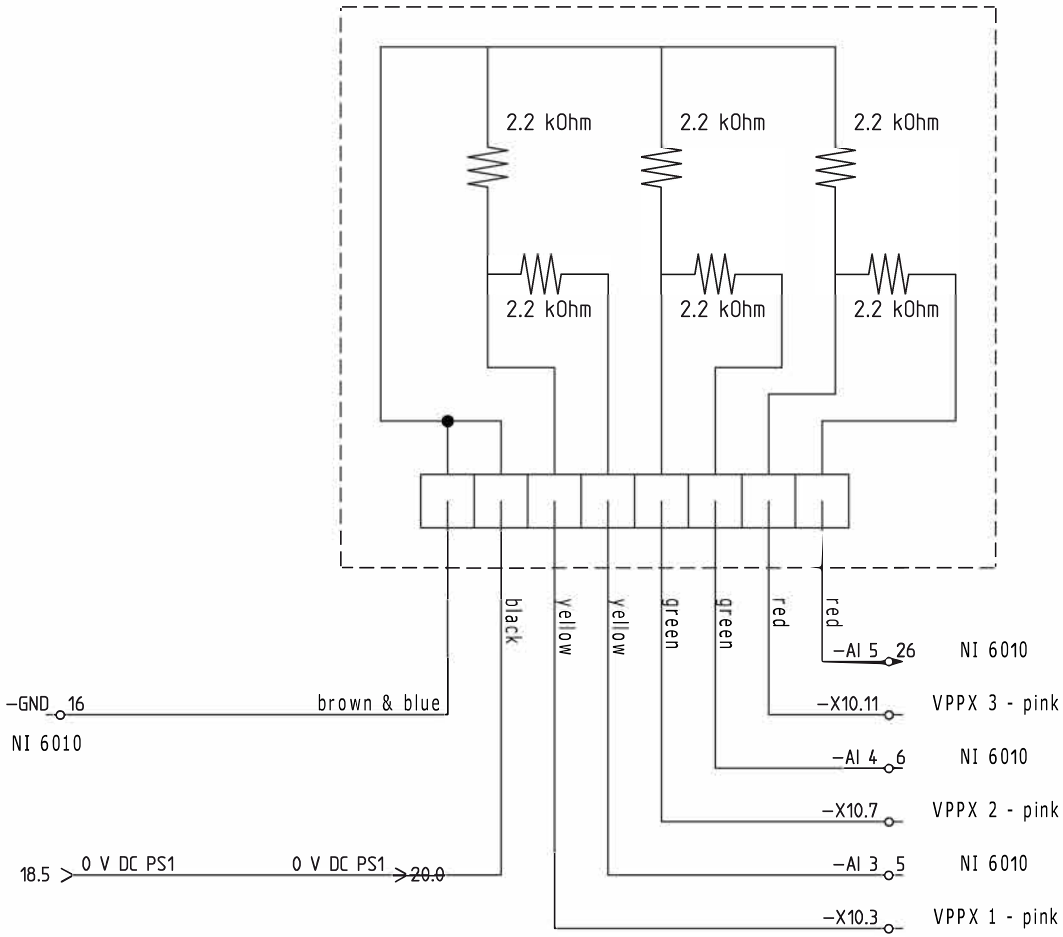
SCHOOL LICENCE

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

ADFEUP

ANALOG SIGNAL CONDITIONING
VOLTAGE DIVIDER 1

Project: Creep	Drawing no.:	Init.:	Rev.:	Sheet: 18
Date: 27/06/2018	Function:	Location:	Total sheets: 20	Next sheet: 19

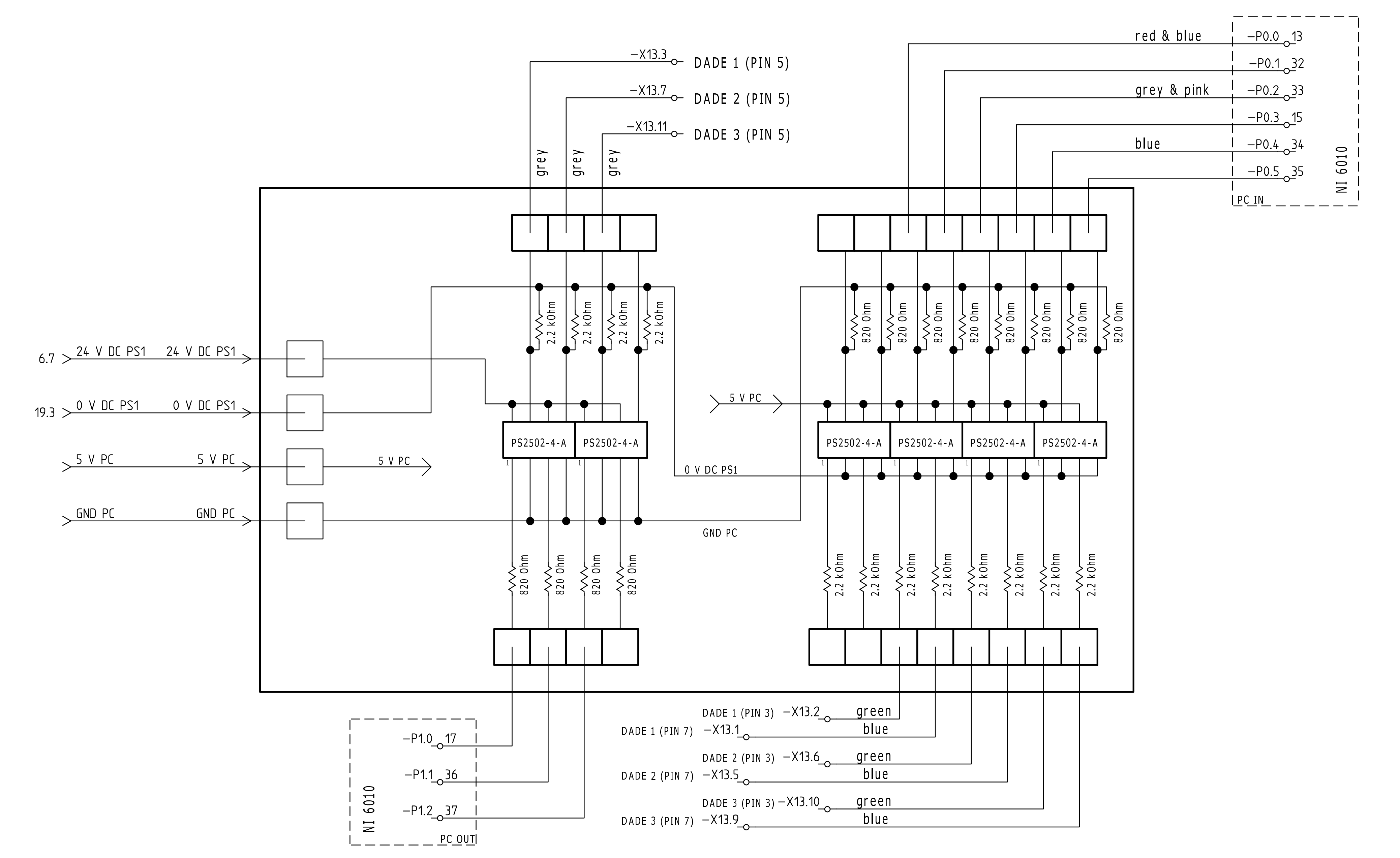


U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

AD FEUP

ANALOG SIGNAL CONDITIONING
VOLTAGE DIVIDER 2

Project: Creep	Drawing no.:		Init.:	Rev.:	Sheet: 19
Date: 13/07/2018	Function:	Location:		Total sheets: 20	Next sheet: 20



U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

AD FEUP

SIGNAL CONDITIONING BOARD 2

Project: Creep	Drawing no.:		Init.:	Rev.:	Sheet: 20
Date: 06/08/2018	Function:	Location:		Total sheets: 20	Next sheet:

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