

Politecnico di Torino



Department of Control and Computer Architecture
MASTER OF SCIENCE IN MECHATRONIC ENGINEERING

MASTER DEGREE THESIS

Analysis of a binder jetting 3D printer and temperature control of print-bed



CONCR3DE

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2019

Acknowledgments

I would like to thank Eric Geboers and Matteo Baldassari to give me the opportunity to work in Concr3de B.V., in an experience that I will not forget that helped me to develop my skills in an amazing working environment.

Thank you to Evert Kranendonk to have been my supervisor, he supported me a lot during my whole internship experience. I am grateful with the working team for having been not only my colleagues but also good friends.

A special thanks goes to Professor Marcello Chiaberge to have been always available during my entire academic path.

Finally, I have to express my profound gratitude to my parents for providing me continuous encouragement and for always being by my side in every choice that I made. Thank you.

Davide Longhitano

Abstract

Binder jetting 3D printing is a powerful technology of additive manufacturing that enable to create object with complex geometry. Concr3de B.V. is a start-up company based in Rotterdam (Netherland) that are developing a 3D printer by using this technology with concrete as base material. The freedom to use different powder mixes allows creators to obtain stone parts with high precision, durability, sustainability and good physical and chemical properties.

The goal of this thesis is to give an overview of binder jetting 3D printing technology used by Concr3de and a first approach on the temperature control of print-bed is investigated. Certain materials have a positive effects of increasing temperature during printing process obtaining an increasing of reaction rate between powder and binder that could lead improvement of final short and long term strength of printed object.

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Introduction

This thesis is based on the internship experience in Concr3de B.V. start-up. Being a small company the working environment allows to investigate different aspect of the project. In the first two chapters a general explanation of additive manufacturing technology in presented evidencing more on technologies used by Concr3de that is focusing on research and development of materials, powders, geo-polymers, motion system, mechanical design, fluid and inkjet system to develop a reliable 3D printer to give the opportunity to architects, company and creators to make complex stone parts, restore old buildings, improving performance, reducing material and production costs.

During the internship one of the assignments was to give an approach to develop temperature control system of print-bed to see if the printed object can improve some physical properties. The system is proposed considering the cost and pre-assembled mechanical design constraints.

A PID control is implemented by using PLC Programming through Tia Portal software, integrating the controller in s7-1200 Siemens PLC. It controls a heater lamp that heat up the surface and an infrared sensor measures the temperature of print-bed. The control system is tested in a design simulation that helps to verify and validate the intended function of a product under development, as well as the manufacturability of the product. Before to test overall system on printer, sensor and IR lamp are tested separately and subsequently system is tested in static condition. The fifth chapter presents various tests on printer. The spreader system, where the lamp is attached, and movement of Y axis is analyzed to activate the temperature control only during spreading operation in the printing side curing the printed layer in order to facilitate the hardening process between binder and powder. PID control of lamp has to be as fast as possible because the lamp is moving over the surface during spreading operation and it has to be able to heat up uniformly the printing bed side in a short time.

1. Presentation of Concr3de

1.1 History and presentation of the company

CONCR3DE is a Dutch company based in Rotterdam (Netherlands) focusing on the development of additive manufacturing automation. Concr3de is based in RDM (Rotterdamsche Droogdok Maatschappij), in the middle of port area of Rotterdam, a technology hub with over 40 innovative companies working on renewable energy, robotics and technologies. CONCR3DE is a start-up company with a mission to transform the construction industry by combining additive manufacturing and reuse of waste materials. The start-up was founded in 2016 by Eric Geboers and Matteo Baldassari with a background in architecture and design. In 2017, the company developed and proved the use of its inorganic polymer liquid binder for geopolymer printing. In 2018, the company is aiming to develop produce scalable 3D printer for industrial and civilian use. They focus on high end binder jetting 3D printing using sustainable concrete, to scale the design possibilities in sustainable concrete architecture, interior and building.



Figure 1.1: Concr3de Logo

1.2 3D Printing overview

The latest industrial revolution, Industry 4.0, is encouraging the integration of intelligent production systems and advanced information technologies. Additive manufacturing is considered to be an essential ingredient in this new movement. It regroups a broad range of technologies and processes to realize the manufacturing of object. Additive manufacturing and in particular 3D printing industry is receiving an incredible attention in the last years. It is a suite of innovative technologies that fabricates three-dimensional objects directly from digital models through an additive process.

The term Additive Manufacturing refers to a whole set of different production techniques, able to process different groups of materials like plastics, concrete, metals and ceramics. The American Society for Testing and Materials (ASTM) defines it as ‘a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining [1].

3D printing finds applications in various sectors such as construction, automotive, architecture, medical, certain aerospace industry, electronics products, industrial machines and biotechnologies.

The International Organization for Standardization (ISO) / American Society for Testing Material (ASTM) has classified the additive manufacturing processes into seven categories:

- Binder Jetting (BJ), a liquid binder jet printed onto thin layers of powder
- Direct energy deposition (DED), focused thermal energy melts materials during deposition
- Material extrusion (ME), a material is selectively pushed out through a nozzle orifice
- Material Jetting (MJ), a droplets of build materials are deposited

- Powder bed fusion (PBF), the thermal energy fuses a small region of the powder bed of the build material
- Sheet lamination (SL), a sheets or foils of materials are bonded
- Vat photopolymerization (VP), a liquid polymer in a vat is light-cured

In terms of materials a variety of technologies are used such as polymers, metals, composites heat source like power laser and microwave radiation [2]. The use of these technologies is dependent on the type of additive manufacturing process used and the additive process chosen defines the modules of automation.

Additive manufacturing has been identified as having the potential to provide a number of sustainability advantages, like:

- Reduction of material consumption as generation of less waste during manufacturing
- Speed of production
- Environmental sustainability
- Direct production from 3D CAD models and no switch over cost
- Customized products are economically attractive relatively to mass production
- Ease on realizing complex structures
- Capability to optimizes geometries and create light weight component
- Reduction in transportation in the supply chain

Currently available additive manufacturing techniques can be economically convenient and compete with traditional processes for small to medium batch production. The machine cost per part is a major component of total cost, but the cost will decrease as additive manufacturing becomes a more commonly used production technique. Furthermore, it is expected to become more cost effective as larger production volumes become more economically feasible than at present [3]. Additive Manufacturing will play a part in the transition towards a more sustainable industrial system as the application of 3D printing technologies

creates opportunities for more sustainable production and consumption and also provides opportunity for organizations to experiment with their business models. Market size of Additive manufacturing is growing every year of 33% and according with Wohlers Report the worldwide 3D printing industry is now expected to \$3.07 billion in revenue in 2013 to \$12.8 billion in 2018 to exceed \$21 billion in worldwide revenue by 2020.

1.3 Concr3de Technology

Concr3de has chosen to develop a printer using geopolimer products from powders as base material. The printer use a binder jetting method and it is built up from many thin cross section of the 3D model.

Binder jetting is a 3D printing process that creates objects by depositing binder layer by layer over a powder bed. Binder is ejected in droplet form onto a thin layer of powder material spread on top of the print-bed. This process can creates accurate structures with complex geometries by depositing binder liquid selectively into to powder bed to bind powder where it impacts the bed. This method is capable of producing building components with fine details and intricate shapes. There is a demand in construction industry for such components which can only be made with expensive formwork systems. Binder jetting technique can produce robust and durable components at a reasonable speed to satisfy this industrial demand [4]. The advantages compared to material jetting are the mix of powder and binder on demand and inkjet precision.

Normally, printers are equipped of 3 modules:

- Binder jetting module, the purpose of binder jitter modules or print-head is to selectively deposit onto the powder bed a liquid; this process requires a high mechanical precision; the inkjet system moves across a bed of powder and selectively deposit a binder liquid on surface; the ink and powder connect and form a strong mineral bond.
- Fluid delivery system, it provides and maintains a flow of fluid to the binding jitter modules to enable jetting and/or cleaning of the nozzles' jetting assembly
- Motion module, it manages the tasks necessary to print and it is composed by Siemens PLC s7-1200, servo motors, step motors, motor controllers, relays and sensors.

The communication between the three modules are accurately configured to provide binder solution to the jetting assembly that needs position feedback from motion control unit to jet to the expected position. Each module is equipped with a control board to communicate to control interface.

This technology allows to quickly produce large scale parts with completely free in geometry with a resolution of 100 microns and 400 DPI, printing several mixes and compositions to achieve different colors and mechanical performance. Just minutes after printing, the printed parts are cured and can be taken out of the printer.

1.4 3D Printer development

Concr3de started investigating the old Z310 powder printer that used a very common concept called 3D power bed and inkjet head printing. This concept was applied to the prototype.

The first prototype made was “Mini-Rhino”, a testing machine with printing size 300x300x200 mm mainly used for research and development. As first developed printer, Mini-Rhino serves multiple purposes:

- Proof the concept
- Build a solid 3D printer to reassure investors
- Improve material properties
- Establish design requirements for scalable projects
- Acquiring knowledge of printing process
- Define printing protocols
- Ink supply technologies
- Proof the concept with binder jetting technologies
- Define process for development of binder solutions
- Review issues and point of improvements

The second printer built is an improvement of the previous machine. Starting from the results obtained with Mini-Rhino they created “Armadillo” in two version, black and white.

Armadillo white is an open system, mainly for R&D, made to design, develop and test custom 3D printed materials with a fully accessible system. Researchers can customize powder and binder compositions as well as control material properties of the 3D-printed end result, control mechanical performance, porosity, density, durability and other specifications to design their own material.

The machine has a large work space and high precision inkjet system. Because of the robustness of this printer, it can handle a great variety of powders. Printer dimension is 1700x1200x2400 mm, print-box dimension of 380x300x300 mm, print-head precision of 400 DPI and layer height of 40-500 μm .

Armadillo black is dedicated for prototyping and continuous production of parts in stone and concrete. Armadillo black is designed for architects, it has a robust and high capacity inkjet system that allows the designer to create any shape with high precision, a range of scale models from 1:100 to 1:5. Print-box dimension is 380x300x300 mm and a printing speed of 4 cm/hour.

The main goal of company is to get printer even bigger, building a huge machine fully automated with 540 liters of volume and a fully integrated work flow including powder handling, data processing and process monitoring. Thus they are starting to design the Hippo printer, a large scale 3D printing system that can improve the production system whit the fully integrated manufacturing system. A print box dimension will be 650x1400x800 mm.



Figure 1.2: Concr3de Printers development

1.5 Scope of project

“create the future or rebuild the past”

The start-up company wants to give a certain level of freedom that is unique creating environmentally friendly structures using their innovative technology and materials. It can be reached thanks to its technology that gives a variety of opportunity in term of powder mixes and the high mechanical performance that allow to obtain objects with a really high quality.

Create the future or rebuild the past means to design freedom and sustainability, to allow designer and architects to have inexpensive molds, fast manual labor, low waste, creating a better future with reducing prototyping cost of 10 times, iterating 15 times quicker and creating optimized geometry.

Some projects of interest are in:

- *Rebuilding Palmyra:*

Palmyra is an ancient roman city in Syria destroyed by ISIS during a Civil war; the group created a platform where people can remodel the ancient city based on old photos and drawings in 3D. Concr3de technology is the only technology that allows you to print the objects in a real stone material with the precision and geometric freedom that is required. By using this technology a segment of the infamous arch was created, costs were reduced of 25x and rebuilt in 4 hours. [5].

- *Rebuilding Notre Dame:*

Notre Dame has been scared by fire and great part of cathedral in Paris was destroyed. The idea of President Macron is to restore Notre Dame fully and quickly, exactly how it was. Concr3de proposed to collect the ash, the dust and the damaged stone to reuse them and turn them into a 3D printable powder. The powder print will have the color of the Parisian stone yellowish grey, mixed with the charred remains of the wood. They can then use this powder, together with existing 3D scans and directly 3D print the lost parts of the Notre Dame. Concr3de has already reproduced Le Stryge, a demon statue that sits on the roof of the

gothic cathedral in Paris, created by Viollet-le-Duc in the 19th century. The material used was a mixture of limestone and ash, the same color as the yellowish-grey stone of Notre-Dame. Costs and time are reduced, they could start reconstruction almost immediately without need for new expensive and hard to find materials. [6]

- *New Design:*

Concr3de was challenged to print a coral shape lamp with a unique material: salt harvested from the ocean. They created a salt based material system and were able to print object with very low material cost but with high precision. This material allows also to have create different color thanks to some pigments mixes.

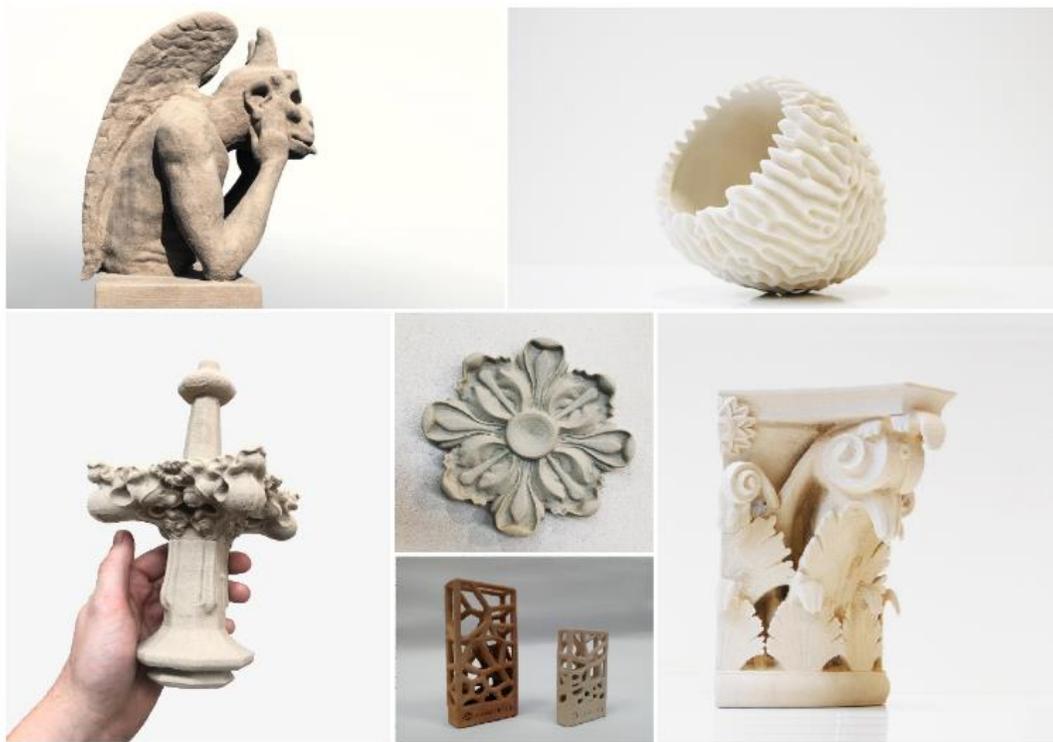


Figure 1.3: 3D Printed Objects Examples

1.6 Market

Concr3de wants to bring powerful high-precise 3D printers to scale the design possibilities in sustainable concrete architecture, interior and building. In the 3D printer market nowadays is hard to sale expensive 3D printer to the wide building market. Concr3de thought to focus marketing and sales on the narrow luxury architecture and interior market where the limitless unique design and piece of art are the main demand. The margin is much higher providing a faster-returning on investment. The target market where Concr3de planned to sell their printer is for:

- Interior design agencies
- Architect agencies
- Building companies
- Custom furniture
- Landscape design
- Restoration agencies and institutions
- Individual designers and architects
- Departments of R&D Universities

A loyalty program for designers and architects can be a good incentive for designing more complex design elements from concrete and as a result, stimulating production orders for these elements. On September 2019 Concr3de will enter in the market fully starting the printer production.

2. Project Overview

2.1 Print Principle

Additive manufacturing for binder jetting applies the following steps:

1. Moving powder spreading to start position
2. Step up the powder bed
3. Spread a layer of powder
4. Step down of the print bed
5. Position wise jetting of binding agent on powder layer
6. Repeat from step 1 till completion of printing
7. Post processing

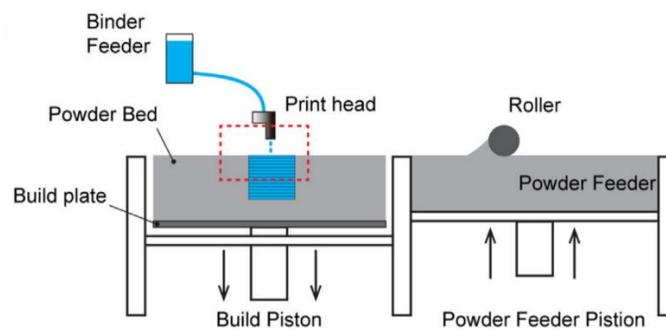


Figure 2.1 [1]: Binder jetting process

Thus, the working principle behind the printer can be described as a system with two boxes of the same size where the powder get transferred layer by layer from the first box (feeding bed) to the second box (printing bed). During spreading operations a roller spreads the new layer and every time a layer is deposited the print-heads spray a binder on the surface. The place where this binder meets the powder it starts hardening the material. They are the parts with the highest required mechanical precision. The part is made on the build platform and made out of tiny layers, approximately 100/200 μm .

The feed platform will move up a layer each cycle, allowing the roller to move the powder from the feed platform to the print platform. To retrieve the part a box can be printed around it and then the print-bed can be lifted and the excess powder can be removed and recycle.

Mini-Rhino and Armadillo printers uses exactly this kind of process. Two platforms are attached to Z actuators and are fitted in the boxes; the plates allow the powder to be pushed up and down which enable the transport of powder layers. The roller is placed inside the spreader system, attached to a carriage on Y actuators and moved over the powder stage, by doing this it spreads a tiny layer of powder from the feeding box to printing box. The print-heads are inside a protective box mounted on the carriage, on the opposite side respect to the spreader, which are moved in the X and Y direction on print-bed. Before the system can run, a home sensor is used to locate the zero position for each axis and the encoder tracks absolute position from then on.

Jetting system consist of two print-heads of 512 nozzles each with a native resolution of 200 DPI. The print-head is designed for binary jetting using an 80-picoliter native drop size with 8 meters per second nominal drop velocity for jetting fluids in the 8 to 20 centipoise range. A piezoelectric crystal is used for drop-on-demand jetting. The 400 DPI maximum print resolution of jetting system consist in to parallel print-heads, knowing the Y axis print-head's nozzle position and the encoder's pulse of axis servo-motor.

To enable splitting from print-heads it is necessary to properly provide fluid to the jetting system. Fluid supply system manage the flow sent to print-heads. Flow management is achieved by creating and maintaining over and under pressure inside the fluid's tank supply. Pressure control enables three actions:

- Feeding: maintaining a constant supply of liquid to the print-heads
- Purging: force supply of liquid to the print-heads
- Meniscus: create a surface tension from the liquid on the PH's nozzle plates

Inkjet system task is not only jet's nozzle jetting the desired liquid, but it has to manage the volume, the velocity and reliability of the spit. The jetting process couples the electrical into the mechanical domain through the piezoelectric actuator, and an electrical signal is transformed into a mechanical deformation of the print-head structure.

Print data are supplied as swaths, corresponding to one pass of the carriage. After each swath, the carriage gantry is stepped forward in the Y direction over the print area. For a 400 DPI print the drop spacing must be around 75 μm ; for the Y axis, this is the mechanical based precision. A magnetic rotary encoder is used to control the servo motor position with a precision of 1 μm . A dedicated port exists on the PCC to ensure encoder pulse reception from the servo motor. It indicates when the print-heads nozzles need to fire on the X axis. The nozzles only need the X axis position in real time, the swath enables to divide an image as multiple pictures with the width of the PH as their maximum dimension. The print-heads should be properly positioned for the next swath picture in the Y axis before moving the Y axis. Repeatability of drop positioning between swaths is important and it is achieved using quadrature signals.

2.2 Print Process

As described in the previous chapter, the Armadillo printer follow the same step for additive manufacturing for binder jetting technologies:

1. Y axis moves powder spreading to start position
2. The Z1 axis step up the feeding bed
3. Y axis is moved to spread a layer of powder from the feeding box to printing box
4. The Z2 axis step down the printing bed
5. Y and X axis move on the printing bed positioning jetting of binding agent on powder layer
6. Repeat from step 1 till completion of printing
7. Post processing: depowder and hydration

After printing print-bed is stepped downward in the Z direction. Printing can be done in one or both directions.

The process is repeated till completion of printing, it can takes maximum 6 hours long, depending how bigger is the object to print. Each box is 300x300x300 mm size, and it can contain around 35-36 Kg of powder.

After printing just like an archeologist the user has to dig and reveal the result. A depowder process is necessary to dust off the result and the powder not used during the printing process can be fully reused in another print.

Sometimes for certain material a hydration process is necessary, by using acetone or water solution; it influences some chemical effects on the printed object including changing in structure and especially in short and long term strength of product.

Extra care should be taken when handling and using the print-heads, since the electronics of the print-heads and the print-heads itself are delicate and fragile. When done printing they should be cleaned and flushed, to prevent the powder that has attached itself to the print-heads to harden, which results in blockage of

the nozzles. It is also advised to clean the surface of the machine after printing so that excessive powder doesn't damage any moving parts.

2.3 Printer Architecture

The general diagram of the software communication with electronics and hardware divided in front end, back end and hardware is showed below:

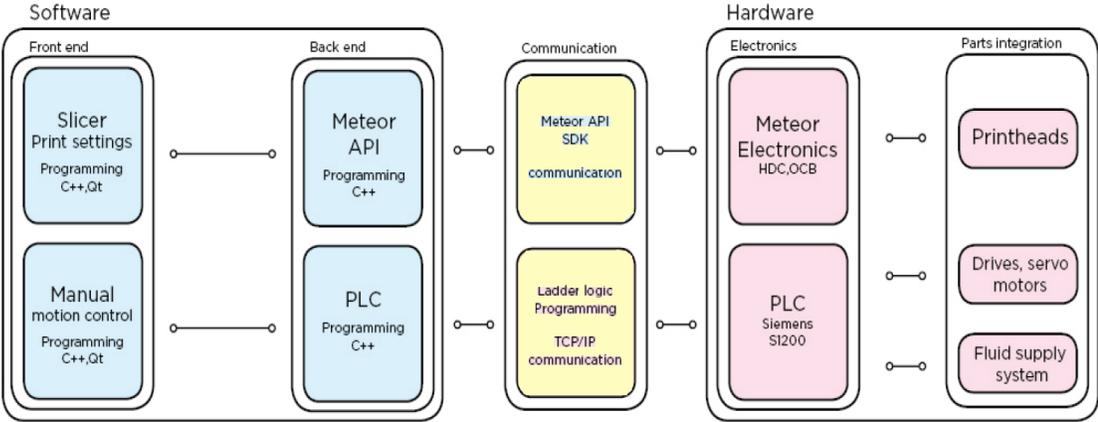


Figure 2.2: Mini-Rhino printer architecture

The software is a stand-alone application to control and slice the 3D models, control machine motion system, control piezoelectric print-heads and ink supply systems.

Concr3de uses its own slicer software called Noah that accepts any .stl, .obj or other mesh file. Noah allows to print multiple models at once and modify printing settings. The interface allows to first choose the material system and consequently import the CAD 3D model and position them in the printing space automatically using a nesting algorithm based on bounding boxes. The interface allows also the user to control manually 3D models with standard function like move, scale duplicate, rotate and so on. The interface has also a section dedicated to manual control of the machine, this part of the software allows to control manually the printer and for instance push a button to spread the powder for

testing, move the Y axis, move home the print-head carriage, purge print-heads, move building box up or feed box down. These functions are useful to control the machine manually during maintenance, when loading the feeding box with material before the print starts or afterwards when the print is finished and it has to be removed from the printing box. During the printing a window pops up showing the layer currently printed and the status of the process.

A Siemens PLC controls drive, servo motors and fluid supply system. The PLC is programmed through the software TIA portal using a ladder diagram programming language that allows to create basic function blocks. The PLC module provides motion control for:

- X axis servo motor
- Y axis servo motor
- Z1 and Z2 axis step motors
- Rolling recoater
- Spreading roller motor
- Heater
- Sensors: temperature, humidity, homing, print-bed temperature and door.

Mini Rhino design needed to have homing and position sensors to inform PLC where the axis is. Armadillo printers use different axis controllers with no need of homing sensors.

The function blocks are programmed by C++, establishing a TCP/IP communication to talk directly from the programming interface to the PLC to create complex machine tasks. The axis controllers of Armadillo communicate with PLC through PROFINET protocol able to control equipment with a particular strength in delivering data under tight time constraints.

The fluid supply system is controlled by a Magnajet software programmed in C#. The transition from C# to C++ was done integrating Qt GUI with C++ language.

It is uncommon to have C++ and ladder code to manage routine for a PLC. The reasons of this choice are mainly for a fast development of motion control, an easy implementation of C++ control motion routine and modification.

Piezoelectric print-heads and electronics of the print-heads are controlled by a proprietary software of Meteor. The concrete main front end app allows to control the motion system and the meteor API to program custom routines for the machine according to the front end application inputs. The meteor API is programmed in C++ and communicates directly with the print-heads through a print controller card and the head driver card. The print controller card communicates with the PC and it receives the images from the PC. It then calculates the position of each drop required for the received image. In order to know where the actuator of the print-head is positioned and how fast the print-head is going, the PCC-e receives an encoder input from the PLC. In this way the print controller card can adjust the firing speed of the print-heads. In this case there are more than one print-heads in line, it also has to calculate which print-head needs to fire where and when, to print the image. The information from print control card is then transferred to the head driver card. This is a controller board which can control just one print-head. The head driver card receives the printing information for the print-head and then executes this at the specified position and with the right amount of liquid.

2.4 Materials R&D

Concr3de is able to 3D print geopolymers. The company has defined their own geopolymer powder composition and binder solution that once mixed it gets solid. They can create several high end stone materials with high strength durable and sustainable properties.

Concrete is the most widely used building material obtained by hardening the mix made of coarse and fine aggregates, cement as the binding material, and water. The basic properties of concrete depend on the quality and properties of cement, w/c ratio and the homogeneity of compaction. Compressive strength is one of the most important properties of concrete. Different types of admixtures are used to control physical and mechanical properties of concrete mixes and hardened cement paste. It is important to analyze the effect of such hardened concrete on physical and mechanical properties of concrete in order to reach the best performance of hardened cement paste [7].

As powders, Concr3de normally use:

- OPC, Portland cement
- Limestone cement
- Fly ash mixed cement
- Calcium alumina cement

The composition of the binder is mainly water or an aqueous commercial clear solution with the viscosity similar to pure water like:

- Potassium silicate solution
- Cellulose ether
- Hydrolyzed polyacrylamide

Rather than printing with polluting plastics or cement, Concr3de uses industrial byproducts to 3D print high strength, stone-like parts, and the materials have a really low carbon footprint and 81% less CO₂ solution compared to standard portland cements.

Concr3de has created different materials and they can offer their own standardized materials:

- White Carrara, Limestone (beige color), Grey Granite, Black Granite: they have the same properties:

- Compressive Strength: 20 MPa
- Tensile Strength: 5 MPa
- Bulk density: 1200 Kg/m³
- Printed Density: 1700 Kg/m³
- Bag Size: 30 Kg
- Min. wall thickness: 3 mm

- Foundry Ecosand: being a sustainable and circular product, no furan, phenolic and urea resin, it has:

- Bulk density: 1200 Kg/m³
- Printed Density: 1650 Kg/m³
- Bag Size: 30 Kg
- Max. Temperature: 1650°C
- Min. wall thickness: 2 mm

They continuously do research and develop of new materials for 3D printing or adapting existing material systems for unique application, optimizing material properties, performance and behavior. If their standardized do not meet clients requirements, clients can develop own material by using Armadillo White because of the robustness of the printer it can handle a great variety of powders.

3. Temperature Control of print-bed

3.1 Purpose of heating up surface of print-bed

Concrete normally uses different type of powder like OPC (portland cement), Calcium Alumina Cement or fly ash mixed cements, but not all cement has a positive effect of heat. Most of cements having a limestone as one of the component will have positive effect of increasing temperature. For example, OPC or limestone cement have positive temperature effect. The increasing of temperatures will result in physical and chemical transformations in the material. Various researchers have studied the microstructure and hydration to explain these effects, main benefits to heat up this kind of powders on print-bed are:

- Increasing reaction rate between powder and binder, reaction between them can happen faster promoting the hardening process
- Accelerate hydration during first couple of days, thereby enhancing the early strength development
- Improving of compress strength of printed object

On contrary, elevated temperatures (40°C) generally accelerate the early-age strength development of mixed cements, while reducing the long-term (90 days) strength development. The loss of long-term strength is induced by both physical effects and chemical effects. The physical effects are an increase in porosity and an increased incidence of micro fracture in cement paste and the chemical effects include changes in the structure of the hydration products and the loss of water in concrete [8]. Therefore, temperature of powder must be increased no more than 25-30%, usually around 27 – 32 °C depending which mixes of cement is used.

3.2 Temperature Control System Overview

A control system is a device that manage, command, direct or regulate the behavior of a process systems. It is usually a feedback system having a control loop, including sensors, control algorithms and actuators, and is arranged in such a fashion as to try to regulate a variable at a set point or reference value.

In a control loop, the system deviation between set-point and process value is determined by the controller and a manipulated variable is derived from this deviation. The manipulated variable acts on the controlled system via an actuator

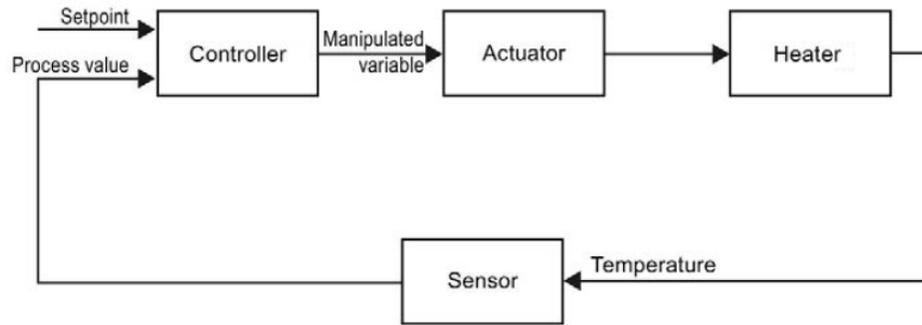


Figure 3.1: System Control Loop

The controller can be of any type, but in this application a PID controller will be used. Proportional-Integral-Derivative (PID) control is the most widely used control method in industrial and academic applications due to its simplicity and efficiency. A PID controller acts according with this equation:

$$u(t) = K \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt} \right)$$

The proportional part acts on the present value of the error, the integral represents an average of past errors and the derivative can be interpreted as a prediction of future errors [9].

In the temperature control system of print-bed, a sensor will measure the temperature of print-bed and transfer the value into a controller that compare the

current temperature with the given set-point and transfer the value. The controller compares the two values and calculates an output value for controlling a heater that heat up the surface.

In this application a Programmable Logic Controller by Siemens is used to implement the PID controller. PLC are widely used as electronic device for automation of industrial processes, such as control of machinery on factory assembly lines.

3.3 PLC Programming: PID_Compact

A closed-loop control system is implemented by the s7-1200 Siemens PLC by using a 1214 DC/DC/DC CPU, with the aid of the “PID_Compact” block. The PC station is used for visualizing the control loops and the field PG through Tia Portal for commissioning the application.

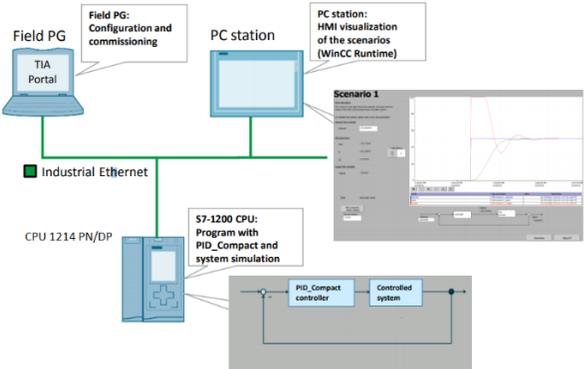


Figure 3.2: HW Schematic

The PID_Compact instruction is used to control technical processes with continuous input and output variables.

The PID (Proportional/Integral/Derivative) controller measures the time interval between two calls and then evaluates the results for monitoring the sampling time. A mean value of the sampling time is generated at each mode changeover and during initial startup. This value is used as reference for the monitoring function and is used for calculation. Monitoring includes the current measuring

time between two calls and the mean value of the defined controller sampling time.

The PID controller uses the following formula to calculate the output value for the

PID_Compact instruction:

$$y = K_p \left[(b \cdot w - x) + \frac{1}{T_I \cdot s} (w - x) + \frac{T_D \cdot s}{a \cdot T_D \cdot s + 1} (c \cdot w - x) \right]$$

y	Output value	x	Process value
w	Setpoint value	s	Laplace operator
K _p	Proportional gain (P component)	a	Derivative delay coefficient (D component)
T _I	Integral action time (I component)	b	Proportional action weighting (P component)
T _D	Derivative action time (D component)	c	Derivative action weighting (D component)

where:

- K_p is a proportional coefficient, it makes the action of system sensitive, faster and steady state control reduced; if K_p is too large the system could become unstable, if K_p is too small the system will suffer from slow movements. An increase in the process value is reached by an increase in the PID output value
- T_I determines the time behavior of integral action and it determines the system stability; small T_I leads to unstable system but it could remove the stable state error and improves the control accuracy of the system
- T_D determines the time behavior of the derivative action and it could improve the dynamic features; T_D large leads to large overshoot and short adjustment time, if it is small will have large overshoot and large adjustment time, but with a proper T_D reduces overshoot and adjustment time

- a is the derivative delay coefficient and it delays the effect of the derivative action; if it is:
 - = 0.0: the derivative action is effective for one cycle
 - = 0.5: useful for controlled system with one dominant time constant
 - > 1.0: the effect of derivative action is delayed
- b is the proportional action weighting and it may weaken with changes to the set-point; it has values between 0.0 and 1.0, if it is:
 - = 1.0 proportional action for set-point change is fully effective
 - = 0.0 proportional action for set-point change is not effective
- c is the derivative action weighting and it acts as the proportional action weighting but for the derivative action.

The controller is a PIDT1 type with anti-wind up function, and the algorithm is implemented in this way:

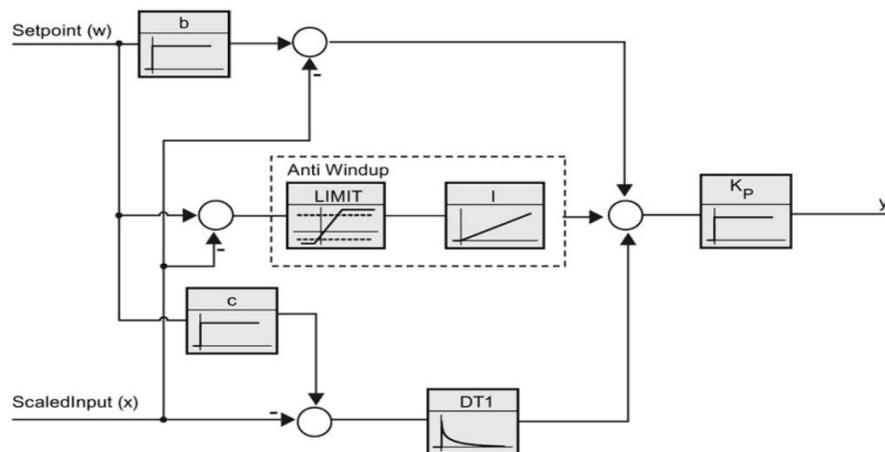


Figure 3.3: PIDT1 scheme of PID_Compact

When the output of controller is saturated, integral action can continue to integrate the error and the integral term continues to grow, but this balance does not produce no effect on the command variable, this phenomena is called wind-up. The anti- wind-up block avoids this problem [10].

The value y at the output parameter Output is transformed into a pulse sequence that is Output_PWM by means of a pulse width modulation. The PID algorithm sampling time is determined during pre-tuning or fine tuning. If manually setting the PID parameters, the PID algorithm sampling time has need to be configured.

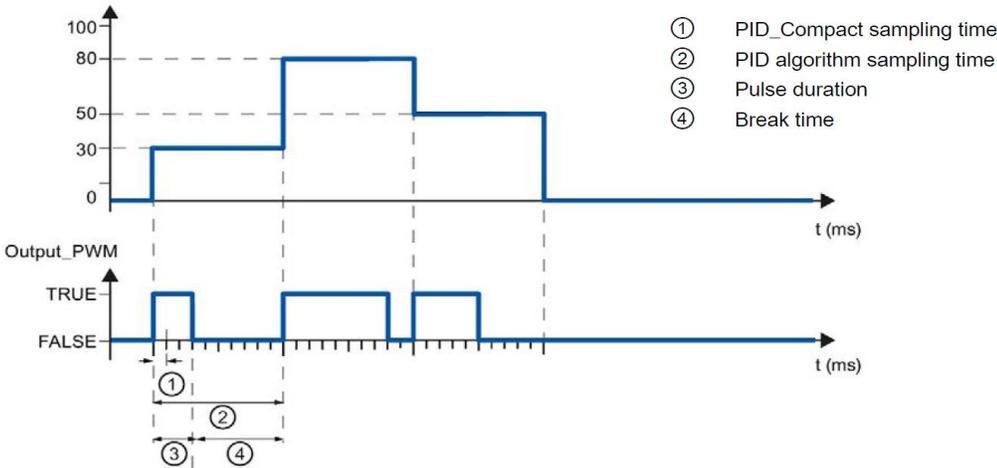


Figure 3.4: PWM output of PID_Compact controller

Output is calculated in the PID algorithm sampling time, Output_PWM is output in the PID_Compact sampling time. The PID_Compact is called in a cycling interrupt and the PID_Compact sampling time is equivalent to the cycle time of the calling OB. This relationship must be taken into consideration designing the controller:

$$T_1 \leq 0.1 T_2$$

Where T_1 is the PID_Compact sampling time (called in the cycling interrupt) and T_2 the PID algorithm sampling time.

The pulse duration is proportional to the value at Output and is always an integer multiple of the PID_Compact sampling time.

The "Minimum ON time" and the "Minimum OFF time" are rounded to an integer multiple of the PID_Compact sampling time. A pulse or a break is never shorter than the minimum ON or OFF time. The inaccuracies that causes are added up and compensated in the next cycle [11].

3.3.1 PID_Compact instruction

The PID_Compact instruction provides a universal PID controller with integrated self-tuning for automatic and manual mode. Instruction block of PID_Compact in LAD/FBD (Ladder logic and functional block) and SCL programming are:

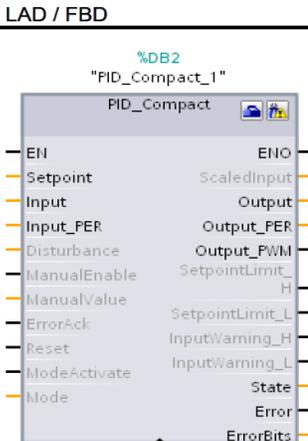
LAD / FBD	SCL
	<pre>"PID_Compact_1" (Setpoint:=_real_in_, Input:=_real_in_, Input_PER:=_word_in_, Disturbance:=_real_in_, ManualEnable:=_bool_in_, ManualValue:=_real_in_, ErrorAck:=_bool_in_, Reset:=_bool_in_, ModeActivate:=_bool_in_, Mode:=_int_in_, ScaledInput=>_real_out_, Output=>_real_out_, Output_PER=>_word_out_, Output_PWM=>_bool_out_, SetpointLimit_H=>_bool_out_, SetpointLimit_L=>_bool_out_, InputWarn- ing_H=>_bool_out_, InputWarn- ing_L=>_bool_out_, State=>_int_out_, Error=>_bool_out_, ErrorBits=>_dword_out_);</pre>

Figure 3.5: PID_Compact instruction

Instructions of PID_Compact are detailed explained below.

“Input” parameters:

- *Setpoint*, it is the set-point of the PID controller in automatic mode
- *Input*, it has real data type as the source of process value and *Config.InputPerOn* must be set to False
- *Input_PER*, it is used as analog input, as the source of process value, if it is used *Config.InputPerOn* = True
- *ManualEnable*, it enables or disable the manual operation mode:
 - a False to True edge activates “manual mode”, while State = 4, *Mode* remains unchanged; as long as *ManualEnable* = True, the operating mode using a rising edge at *ModeActive* or use the commissioning dialog cannot be changed

- a True to False edge activates the operating mode that is assigned by *Mode*
- *ManualValue*, it is output for manual operation; it is possible to use values from *Config.OutputLowerLimit* to *Config.OutputUpperLimit*
- *Reset*, it restarts the controller:
 - False to True edge:
 - Switches to “inactive” mode
 - Resets the *ErrorBits* and warming outputs
 - Clear Integral action
 - Maintains PID parameters
 - As long as *Reset* = True, PID_Compact remains in “inactive” mode (*State* = 0)
 - True to False edge:
 - PID_compact switches to operating mode that is saved in the *Mode* parameter
- *ModeActivate*, it is Boolean and the PID_Compact switches to the operating mode that is saved in *Mode* parameters

“Output” parameters:

- *Output_PWM*, it is a digital output for pulse width modulation
- *Output*, it is an output value in Real format
- *Output_PER*, it is used as analog output value
- *State*, it indicates the current operating mode of the PID controller; it can be changed using the *Mode* input parameter and a rising edge at *ModeActivate*:
 - State = 0: Inactive
 - State = 1: Pre-Tuning
 - State = 1: Manual Fine Tuning
 - State = 3: Automatic Mode
 - State = 4: Manual Mode
 - State = 5: Substitute output value with error monitoring
- *ErrorBits*, the PID_Compact instruction ErrorBits parameters table defines the error messages that are pending; it is retentive and it is reset upon a rising edge at *Reset* or *ErrorAck*

“*Static*” parameters:

- *RunModeByStartup*, it activates Mode after CPU restart
- *PhysicalQuantity*, it is pre-selection for physical unit value; temperature is selected by default
- *PhysicalUnit*, it is user unit selection; general units is % but for temperature units possible selection are °C (by default), °F, °K
- *SetSubstituteOutput*, it becomes True when there is an error pending, when for example the upper or lower limit temperature are violated
- *SubstituteOutput*, when *SetSubstituteOutput* it True *SubstituteOutput* becomes the new output for safety

“*Config*” parameters:

- *Config.InputPerOn*, it selects which kind of input to use; possible selections:
 - FALSE: “Input” (Real)
 - TRUE: “Input_PER (Analog)
- *UpperPointIn* and *LowerPointIn*, they are integer values converted from the measurement of the input voltage
- *InputUpperLimit* and *InputLowerLimit*, they are real values, they are the range of temperature that is converted from the range of integer input value.
- *OutputUpperLimit* and *OutputLowerLimit*, they are real values, maximum and minimum ON/OFF times for PWM output

“*Retain*” parameters:

- *PIDCtrl*, it contains the actual parameters of PID used in automatic mode, that are *Gain*, *Ti*, *Td*, *TdFIntRatio*, *DWeighting*, *Cycle*

The configuration of the “PID_Compact” technology object defines the function principle of the compact controller. The settings made determine the start values used by the PID controller. In the project tree, opening the object “Technology objects > PID_Compact_1 > Configuration>Parameter view” it is possible to set the start values. They can be adjusted during optimization in the watch-table.

The basic operations of PID_Compact can be summarized in this block diagram:

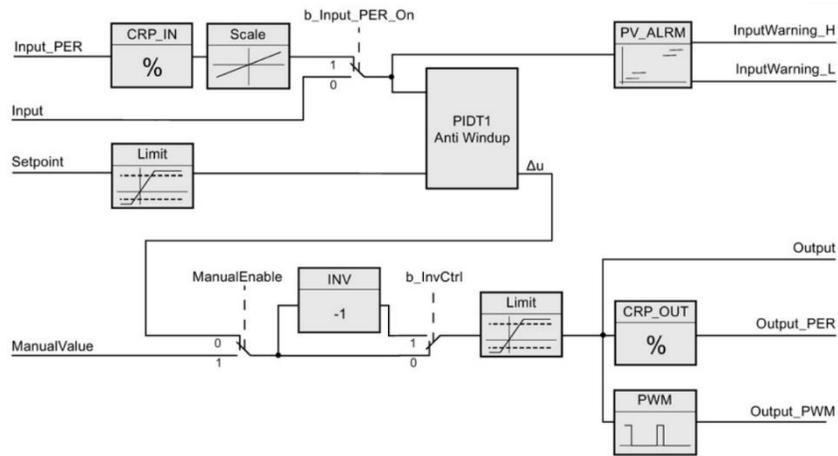


Figure 3.6: Schematic procedure of PID_Compact

In control of temperature of print-bed an analog input (Input_PER) for sensor and a PWM digital output (Output_PWM) will be used.

3.3.2 Commissioning PID_Compact

In the commissioning editor is possible to have STEP 7 calculating the controller parameters via pre-tuning and fine-tuning, if this mode was selected, 'tuning state' shows progress of the status of the system. The settings made determine the start values used by the PID controller. Open the commissioning editor by selecting "Technology objects > PID_Compact_1 > Commissioning".

In the commissioning window many things are possible:

- View setpoint
- View real time measurement of:
 - o Output_PWM
 - o Input_PER
- Edit following parameters:
 - o Set-point in automatic mode

- Disturbance value compensation in automatic mode
 - Enable/Disable manual mode
 - Manually specify the manipulated variable
 - Acknowledgment of ErrorBits and Warning
 - Reset of the compact controller
 - Change operating mode by selecting from “Mode” parameter and activating “ModeActivate”
- Test the configuration of the actual value monitoring editing the upper and lower warning limits

To display set-point and process value (input value) and the output value in a real-time trend, enter the sample time and click the "Start" button.

To tune the PID loop, select either "Pre-tuning" or "Fine tuning" and click the "Start" button. The PID controller runs through multiple phases to calculate system response and update times. The appropriate tuning parameters are calculated from these values. After the completion of the tuning process, store the new parameters by clicking the "Upload PID parameters" button in the "PID Parameters" section of the commissioning editor.

The system can be damaged when “Current value while error is pending” or “Substitute output value while error is pending” happens; in the event of error, it is essential to configure how the controlled system reacts. PID_compact generates an output value in response to error and for instance, if an error occurs during tuning the output value of the PID can be set to 0. The PID mode then is set to "inactive" mode and the status indicates the error.

It is also possible to use Substitute Set-point when CPU is in Run mode by specifying the online status of the controller as “Substitute Set-Point” [12].

3.4 Selection of Sensor

There are many different types of temperature sensor available and all have different characteristics depending upon their actual application. A temperature sensor consist of two basic physical types:

- Contact type: this kind of sensor are required to be in physical contact with the object being sensed and use conduction to monitor changes in temperature; they can be used to detect solids, liquids or gases over a wide range of temperature
- Non-Contact type: they use convection and radiation to monitor changes in temperature; they can be used to detect the radiant energy being transmitted from an object in the form of optical, magnetic or infra-red radiation, for example

Advantages to use a non-contact temperature measurement are because they can measure easily temperature of moving and heated objects and they have a really fast response and exposure time, necessary for control. For these reasons a non-contact infrared sensor is the most appropriate in this application.

Powder on print-bed emits an electromagnetic radiation from its surface, which is proportional to its intrinsic temperature. A part of this so-called intrinsic radiation is infrared radiation that penetrates the atmosphere. Infrared temperature sensors have been successfully used for years in process industries for ongoing temperature monitoring and control. An infrared temperature sensor collects radiation from a target in the field of view defined by the instrument's optics and location. With the help of input optics the emitted object radiation is focused onto an infrared detector. The detector generates a corresponding electrical signal which then is amplified and may be used for further processing. The signal is amplified and it is transformed into a signal proportional to the object temperature. The measuring value may be released as analog signal, which supports an easy connection to control systems of the process management [13].

Consequently, the temperature of the measuring object is mainly generated in three steps:

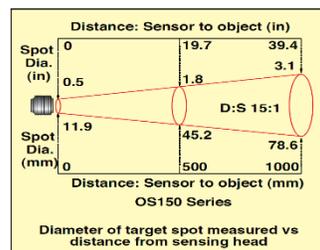
1. Transformation of the received infrared radiation into an electrical signal
2. Compensation of background radiation from thermometer and object
3. Linearization and output of temperature information

Choosing an IR temperature sensor can be a straightforward procedure. Many factors has to be considered:

- *Temperature range*: Infrared instruments are available for low temperature applications to high-temperature applications; in general, the narrower the temperature range, the better the resolution of the output signal for monitoring and controlling process temperatures.
- *Target size*: the area to be measure should fill the instrument's field of view; to collect all the emitted radiation, single wavelength infrared temperature sensors (i.e., point sensors) need a clear line of sight between the instrument and the target.
- *Optical resolution*: It is specified by the D:S ratio, which is determined by comparing the distance from the object to the sensor (D) with the size (diameter) of the spot being measured (S)
- *Target material's emissivity*: The target material's emissivity and surface characteristics determine the spectral response or wavelength needed in a sensor.
- *Response time*: Infrared temperature sensors reach 95% of the final temperature reading much faster than contact temperature; this is particularly important when measuring moving or quickly heated objects
- *Type of output*: The electronics of the infrared thermometer linearize the output signal of the detector in order to generate a linear power signal 0/4-20 mA or voltage signal 0 - 10 V
- *Cost*: infrared sensor, generally, have a huge cost compared with others sensors bur they offer the best solution for this kind of application [14].

It is required to have a sensor that can measure temperature in a small range (i.e. from 0°C to 80°) to have a better resolution. The target size can be 2:1 or 15:1, because the position of the sensor will be close to the print-bed, 10-20 cm high, but the field view could be not huge due to design restriction. The optimum wavelength in terms of material's sensitivity for measuring concrete, sandstone, alumina-silicate powder surface is around 0.9 - 0.96 micron. Response time has to be as fast as possible to have a quickly reading of temperature while it is moving.

IR temperature sensor to measure temperature on print-bed is an OMEGA OS151-LT, a compact non-contact temperature sensor/transmitter. It is a high quality, low cost, compact sensor which measure the temperature of inaccessible or moving object and materials. It has a temperature range from -20°C to 100°C, accurately and consistently, with an outstanding response time of 240 ms. This IR sensor is 2 wire and it transmit the target temperature as a 4 -20 mA output and offer a simple solution for most non-contact temperature measurement applications. This output signal is compatible with almost any indicator, controller, recorder or data logger, without the need for special interfacing or signal conditioning.



Specifications

Accuracy: ±1% of reading or ±1°C whichever is greater
Repeatability: ±0.5% of reading or ±0.5°C whichever is greater

Emissivity: Fixed at 0.95

Response Time, t90: 240 ms (90% response)

Spectral Range: 8 to 14 μm

Supply Voltage: 24 Vdc (28 Vdc maximum)

Min Sensor Voltage: 6 Vdc

Max Loop Impedance: 900 Ω (4 to 20 mA output)

Output Impedance: 56 Ω (voltage/thermocouple output)

Mechanical

Construction: Stainless steel

Dimensions: 103 L x 18 mm D (4.06 x 0.71")

Thread Mounting: M16 x 1 mm pitch

Cable Length: 1 m (3.3') (included) longer lengths available to order

Weight with Cable: 95 g (3.35 oz)

Environmental

Rating: IP65

Ambient Temperature Range: 0 to 70°C (32 to 158°F)

Relative Humidity: 95% max non-condensing

Figure 3.7: Omega OS151 LT sensor specifications

The size of the area (spot size) to be measured determines the distance between the sensor and the target. D:S ratio of this sensor is 15:1, it means that if the distance from the target is 15 mm, the spot diameter will be 1 mm. The spot size must not be larger than the target. It has a good accuracy of $\pm 1^{\circ}\text{C}$ and an emissivity fixed at 0.95, as required. The sensor is designed to operate in ambient temperatures from 0°C to 70°C . To minimize electromagnetic interference or noise, the sensor should be mounted away from motors and generators. All sensors come with a 1m cable and a mounting nut. The sensor can be mounted on brackets or cut outs of design, or by using the fixed and adjustable mounting bracket accessories [15].

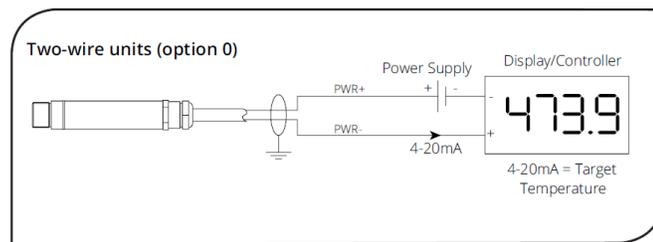


Figure 3.8: Electrical installation of IR sensor

3.5 Selection of Heater

The heater is the process that has to be controlled in the temperature control system to develop for heating the surface of print-bed, but for a good selection of it there are many factors to take into consideration, not only for control but also for heating performance. From engineering perspective, it is important to consider temperature distribution on print-bed during the heating process. Heating performance is influenced by heated body capacity to absorb radiant heat, surface and the distance between the heated body and the heating source.

The absorption of a material is its ability to absorb the energy associated with the electromagnetic radiation that propagates inside it. It is the energy of the photons that is given to the electrons, atoms and molecules of the material. The energy of the electromagnetic field is transformed in this way into internal energy of the material, such as its thermal energy. The absorption depends both on the nature of the material and on the frequency of the radiation, and it can be quantified through electrical permittivity: it is a complex function of the wave frequency, through which it is possible to treat the propagation of the electromagnetic field in means dissipative. Permittivity and index of refraction are related to each other. When analyzing the permittivity from the point of view of the frequency of the field it can present a certain behavior in correspondence of certain wavelengths. In fact, the imaginary part of the electrical permittivity follows a resonant trend at its poles, where it has one or more peaks. In correspondence of these peaks the absorption by the material of the energy possessed by the field is maximum [16]. Furthermore, the Sellmeier's equation describes the relationship between refractive index and wavelength of radiation, for a particular material and it is used to determine the dispersion of energy in the medium; moreover, Snell's law says that at different frequencies, so different wavelength, there are different refraction angles [17].

Concrete use different type of cement as powder on print-bed and water binder. In this application, in correspondence of infrared medium wave radiation, in the range of 1 and 4 μm , it is possible to have a good coefficient absorption, minimum dispersion and low refraction angle.

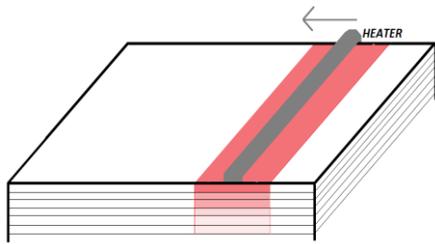


Figure 3.9: Heating process on print-bed

To maximize the heat absorbed from the surface the heater has to be mounted on horizontal position, for the total length of print-bed (350 mm) as shown in the figure. The overall surface will be heated moving the heater together with y axis. Thickness of one layer is less than 1 mm, so heat is also transferred layer by layer, but the heating of surface will happens for every new layer of print cycle.

For testing an infrared (IR) heater lamp 230V 1.5kW from RS is chosen. This IR lamps is simple, effective, reliable, and economical to run and instant radiant heat after power-on. It is economical to operate and suitable for universal mounting orientations. According to mechanical design of system, the length of lamp is 348 mm, as the total length of print-bed. It will be mounted with the spreading system. It can be switched on/off instantly so heat is given instantly [18].

In the final design a different lamp will be used. A good choice could be the IR Lamp with a fast medium wave quartz emitter from Helios Quartz. The IR medium wave radiation is positioned in the range of 1.4 and 1.6 μm . It has a 50 W/cm maximum density of nominal power and 130 kW/m² maximum surface power density. A reflector can be directly applied on the quartz tube, to better convey and focus all the energy emitted on the material.

The IR Fast Medium Wave emitter is the optimal compromise when one specific application requires at the same time the IR radiation of the medium wave emitters and the fast response time in the switching on/off proper. In fact, IR

quartz emitters need short time to switch on and switch off, it reduces the time of operation, optimizes the homogeneity of the heating up of the material and they are easier to control [19].

These kind of lamps are AC, but the output of the controller is a PWM output. The lamp needs to be controlled by a relay able to receive a PWM and then switch on/off the lamp. A power solid state relay as triac output device with Zero-cross circuit is used. This device is used to switch on/off the AC power for the lamp. Control DC voltage, in this application is the PWM output of controller.

The figure below shows the Triac driving circuit:

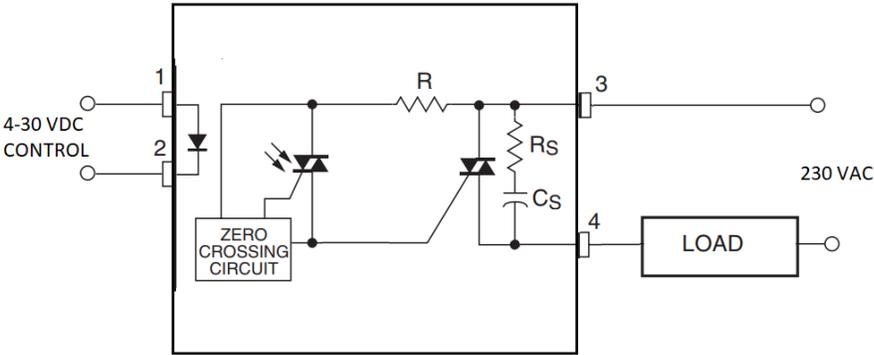


Figure 3.10: Triac Driving Circuit

When the control input is high, the AC current flows through the Triac and goes into the load; when the control input is low, switch is open and the load is off. Trigger always occurs at the zero crossing point. Some loads present a problem because the voltage and current are not in phase with each other. Since the Triac turns off at zero current, it may be trying to turn off when the current is zero but the applied voltage is high. This is usually not a big problem because the Triac will turn off at the next zero crossing of the line voltage, and most loads are not noticeably affected by an occasional single half cycle of applied power [20].

Tests by using oscilloscope are performed to check the behavior of lamp at full power with a 10% of PWM control voltage:

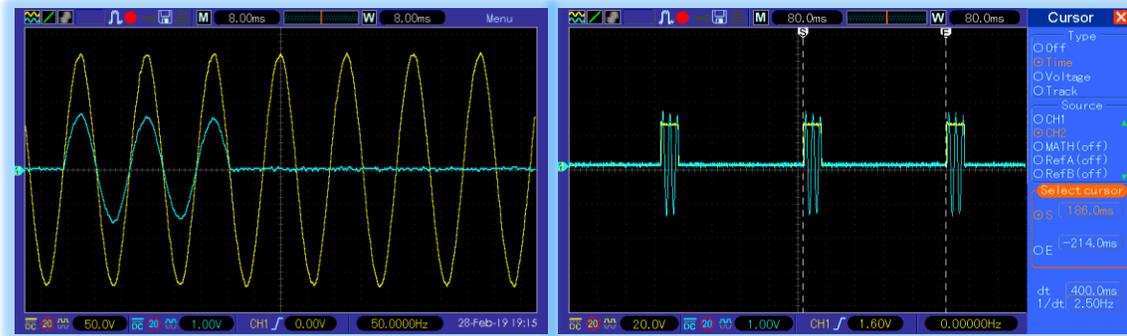


Figure 3.11: AC main and load voltage - trigger test / trigger at 10% PWM oscilloscope test

The AC output of triac and the AC main voltage is checked and the trigger occurs at the zero crossing point (graph on left), current and voltage are in phase with each other. Graph on right shows the PWM control input (yellow curve) and the AC output (blue curve). Interval time of PWM is 400 ms and the lamp is turned on for 10% of PWM (40 ms).

A Triac provides safety isolation from the high-voltage output to the triggering switch and it can work like any other type of overvoltage sensing scheme. Device that is used in this application is a Celduc 12 A Solid State Relay, Zero Crossing, Chassis Mount, Triac, 280 V rms at maximum load [21].

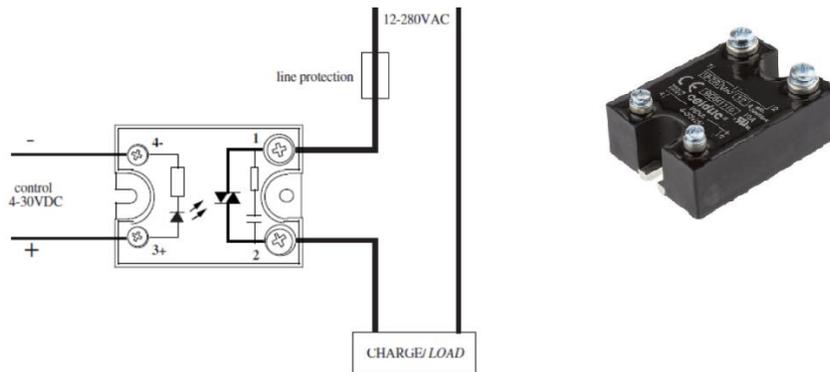


Figure 3.12: Celduc Solid State Relay Zero Crossing - Triac

Specification:

Input:

Control Voltage: 4 – 30 V DC

Control Current: 3 – 30 mA

Internal Resistance: 1000 Ω

Output:

Load Voltage: 230 V AC

Operating Range: 12-280 V AC

Nominal Current: 12 A

Ton time: 10 ms

Toff time: 10 ms

Furthermore, a safety system is implement to protect the IR lamp and device from overcurrent, overload and surge voltage by using a miniature circuit breaker (MCB) and surge protector device (SPD).

3.6 System Design

Assembly the system into printer design is not an easy task, due to limitations of pre-assembled design and considering the purpose:

- Concred3 is interested to heat up the printing part of print-bed, during spreading operation, when the binder is already jetted on the surface for curing the printed layer and to promote the hardening process between the binder and the powder, as explained in the chapter 3.1

Considering the spreading process, Y axis is moved from feeding side to printing side with different velocity. During this process the IR lamp has to be turned ON in a certain step.

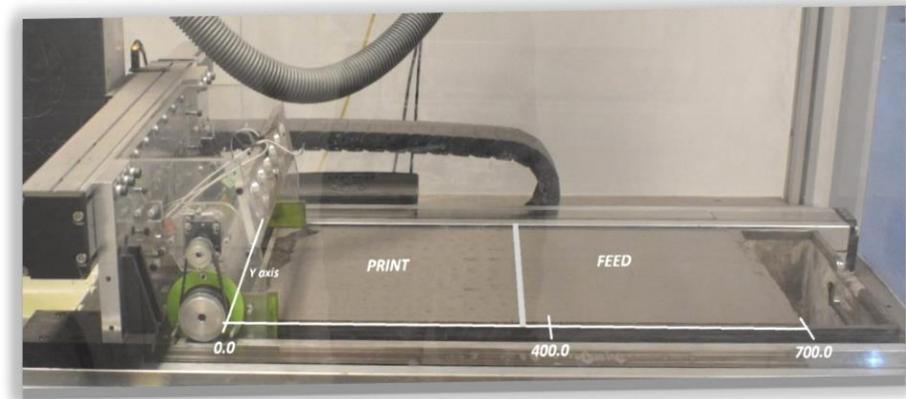


Figure 3.13: Printing and feeding bed

Steps of spreading process:

1. Finish of printing the layer
2. Spread cycle starts
3. Y axis goes back to 700.0 mm position
4. Z1 is moving up
5. Y axis goes from 700.0 to 400.0 mm position with a velocity of 100 mm/s, and the roller is active
6. Z2 axis goes down

7. Y axis goes from 400.0 to 0.0 mm position with a velocity of 40.0 mm/s
8. When Y axis reaches 0.0 mm position, spread process finishes, roller is disabled

The idea is that meanwhile the roller is spreading the new layer, it can heat up the printed layer, but before that roller spreads the new layer. This is possible if:

- IR Lamp is placed after the roller
- IR temperature sensor is positioned between the roller and the IR lamp.

The figure below shows final assembly of IR lamp and IR temperature sensor, integrated in the spreader

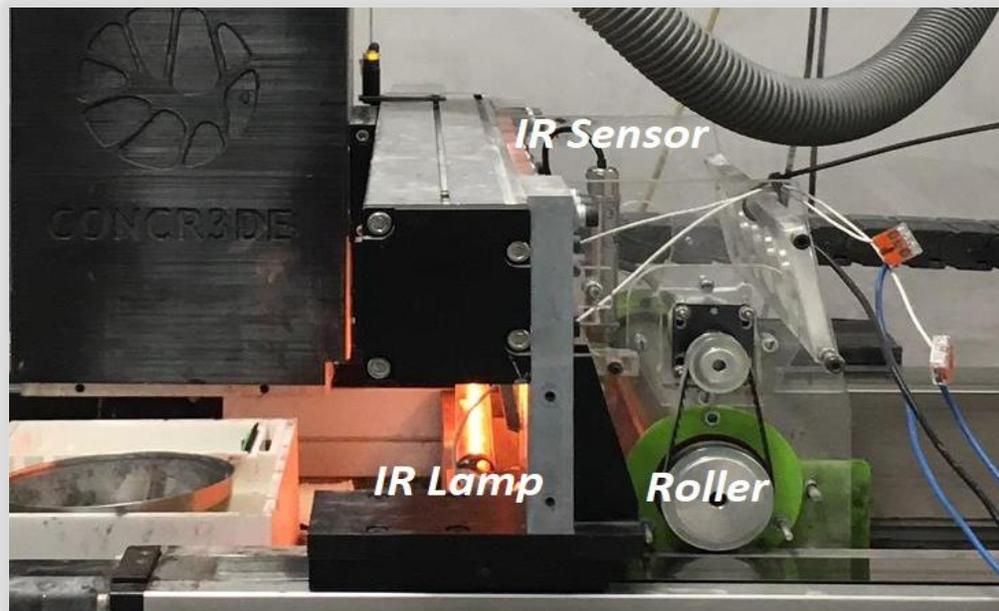


Figure 3.14: System assembly

In this way, IR lamp must be activated in step 7 and sensor measure temperature of heated powder. Sensor is enough far from the roller that spread the “new” powder layer and it is enough far from the IR lamp that is metal covered to not influence the measurement of temperature due to energy transmitted from the lamp.

The distance of sensor from the print-bed is 72 mm, so the diameter spot of surface that the sensor measures is 4.8 mm

IR lamp is 80 mm far from the sensor and it is positioned horizontally on print-bed and the distance from the surface is 20 mm, in order to have a good coefficient of energy absorbed from the powder, thanks also to metal cover.

3.7.1 Electrical System

Overall electrical circuit design is shown in the figure below:

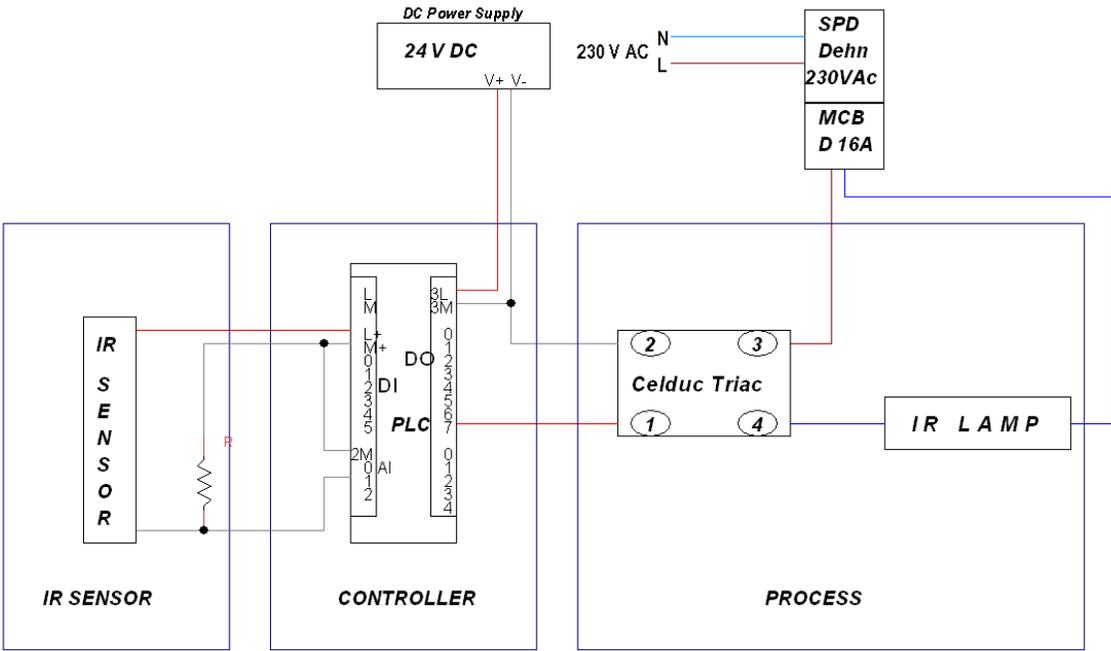


Figure 3.15: Circuit Design

A PLC Siemens s7-1200 with a 1214 DC/DC/DC CPU is used. The Infrared temperature sensor is connected to the analog input AI-1. The solid state relay of triac type connect the PLC for the input voltage control and the infrared lamp as load powered through the main voltage at 230 V AC.

4. System Testing

4.1 Sensor Test

IR sensor will be used as analog input on PLC for the temperature control system, monitoring temperature real time and collecting data to store, in order to see how temperature of the print-bed changes after some hours of printing.

The Omega Infrared Non-Contact Sensor OS152-LT is a 2 wire sensor with current output of 4-20 mA. The sensor can be connected to the analog input signal module of S7-1200 that measure transducer with 0/10 V voltage output.

The figure below shows how to connect the sensor to the power supply and the analog signal module SM 1214C DC/DC/DC

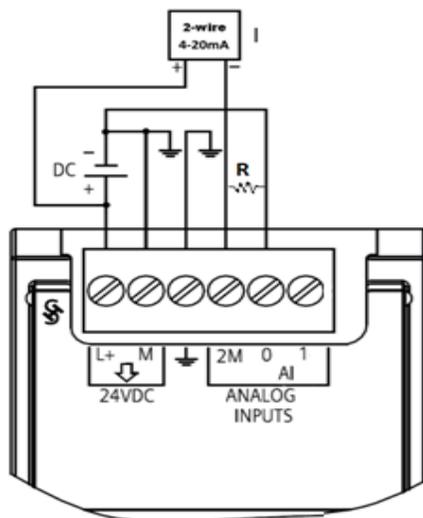


Figure 4.1: Connections

The conversion of current in a voltage is possible by using a resistor. In this case is suggested to use a 500Ω thermal resistor UPF50 Series $\pm 0.1\%$ $0.5W \pm 5ppm/^{\circ}C$. It has an excellent stability, it is not affected by the increasing of the temperature, it has an extremely low TCR down to $5ppm/^{\circ}C$ and high precision thanks to very tight tolerance down to 0.02%, and it is capable of dissipating high power from a relatively small size in a harsh environment conditions. The converted current

in a voltage must be as much as possible precise to have a real measure of the temperature.

PLC converts the voltage measurement into an integer value from 0 to 27648. The range of temperature that the sensor can detect is between $-20^{\circ}C$ and $100^{\circ}C$.

Considering that, conversion of current in a voltage, and the integer value in a temperature is:

- Current → Voltage:
 - Low Limit: $\frac{4 \text{ mA}}{500 \Omega \pm 0.1\%} = 2 \text{ V}$
 - Upper Limit: $\frac{20 \text{ mA}}{500 \Omega \pm 0.1\%} = 10 \text{ V}$
- Voltage → Integer Value:
 - Low Limit: $\frac{27648 * 2 \text{ V}}{10 \text{ V}} = 5530$
 - Upper Limit: 27648

Some tests, by using a multimeter to read voltage and current, have given these results:

Table 4.1: Temperature/Current/Voltage/Integer data

<i>Temperature</i>	- 20°C	0°C	20°C	40°C	60°C	80°C	100°C
<i>Current</i>	4 mA	6.67 mA	9.34 mA	12 mA	14.6 mA	17.3 mA	20 mA
<i>Voltage</i>	2 V	3.34 V	4.67 V	6 V	7.34 V	8.67	10 V
<i>Integer</i>	5530	9306	13082	16589	20365	24141	27648

4.1.1 Real Time Temperature Monitoring

To monitor temperature of powder, a PLC code is implemented in Tia Portal Simatic S7-1200, by using NORM and Scale blocks:

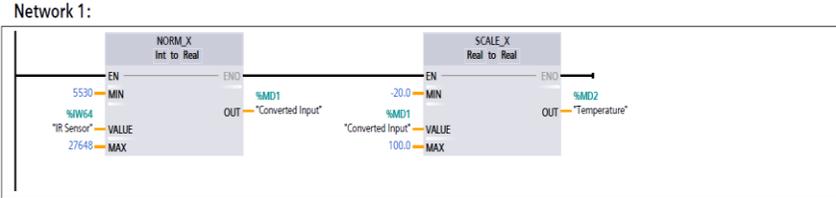


Figure 4.2: PLC code

Network 1 is useful to convert the actual temperature from voltage (integer value) to °C (real value). “NORM_X” normalizes the parameter value that is the analog input of the IR Sensor (IW64), inside the value range specified by the min and max parameters. “SCALE_X” scales the normalized real parameter value data type (Real) and value range specified by the min and max parameters [4]:

$$\frac{(Norm_x_value - Norm_x_min)}{(Norm_x_max - Norm_x_min)} = \frac{(Scale_x_out - Scale_x_min)}{(Scale_x_max - Scale_x_min)}$$

Where:

$$Norm_x_min = 5530$$

$$Norm_x_max = 27648$$

$$Scale_x_min = -20.0^{\circ}$$

$$Scale_x_max = 100.0^{\circ}$$

Norm_x_value is the converted measurement of voltage in integer number and Scale_x_out is the normalized and scaled temperature, real number.



%MD2 output variable (“Temperature”), that is the Scale_x_out value, can be monitored in real time by using the monitoring button in Tia Portal. In this way it is possible to watch the temperature of the powder real time.

4.1.2 Collect Temperature Data

A PLC code is implemented to collect data of temperature measurements, by using DataLogCreate and DataLogWrite in Tia Portal.

In Tia Portal the “DataLog” instructions are used to store process values in log files. These log files are stored on the memory card or in the internal load memory of the CPU. The log files are stored in csv format. The csv files can be accessed via Web server using the IP address of the PLC, they can be downloaded.

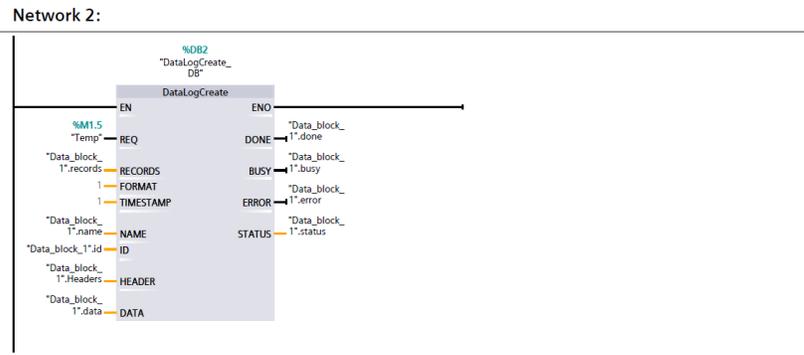


Figure 4.3: PLC Code

The “DataLogCreate” instruction is used to create a data log file in the “\DataLogs” directory in the load memory that specifies the name (“Data_block_1_name”) and the maximum number of data records (“Data_block_1_records”). The “TIMESTAMP” parameter allows to decide whether the date and time stamp will be included in each data record. The data to be logged is specified by the “DATA” parameter. The “HEADER” parameter is used to specify the header (column headers) of the data logged in the data log. Creating the data log file with an assigned name generates a number (“Data_block_1_id”) that identifies this file.

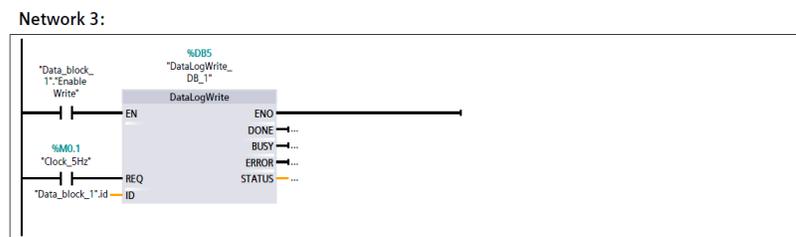


Figure 4.4: PLC Code

The “DataLogWrite” instruction writes a data record to the specified data log. For a “DataLogWrite” instruction to be executed, the existing target data log must be open. “REQ” allows to specify which is the frequency for a new record; in this case is 5Hz, it means that every 200 ms a new temperature is written on file. Use the “ID” parameter to select the data log.

Network 4:

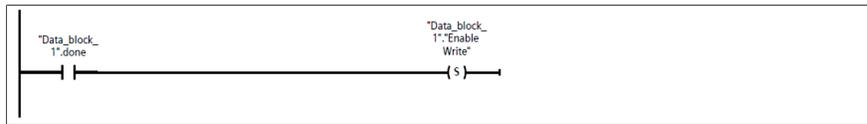


Figure 4.5: PLC Code

This instruction allows to enable the “DataLogWrite” block when “DataLogCreate” is done.

Compiling and downloading the program on PLC Siemens 1214C, when the file “SensorTest” is full with 300 records, the file can be downloaded going on Web Server/DataLog and the data will appear in this way:

	A	B	C
1	1830	2/21/2019,15:08:04,	23,48
2	1831	2/21/2019,15:08:04,	23,59
3	1832	2/21/2019,15:08:04,	23,52
4	1833	2/21/2019,15:08:04,	23,81
5	1834	2/21/2019,15:08:04,	23,66
6	1835	2/21/2019,15:08:05,	23,52
7	1836	2/21/2019,15:08:05,	23,54
8	1837	2/21/2019,15:08:05,	23,51
9	1838	2/21/2019,15:08:05,	23,60
10	1839	2/21/2019,15:08:05,	23,58

Figure 4.6: Temperature data

In the columns appear the number of the record (A), data and time (B) and temperature measured from the sensor (C).

4.2 IR Lamp Test

Testing IR lamp in static condition, the code implemented in Tia Portal allows to turn ON the lamp for 10 seconds at full power, measuring through the sensor how much the temperature of the powder increase, collecting data on csv files to obtain data to be able to get the a mathematical description of the process, according with Ziegler-Nichols method design approach.

The PLC code is:

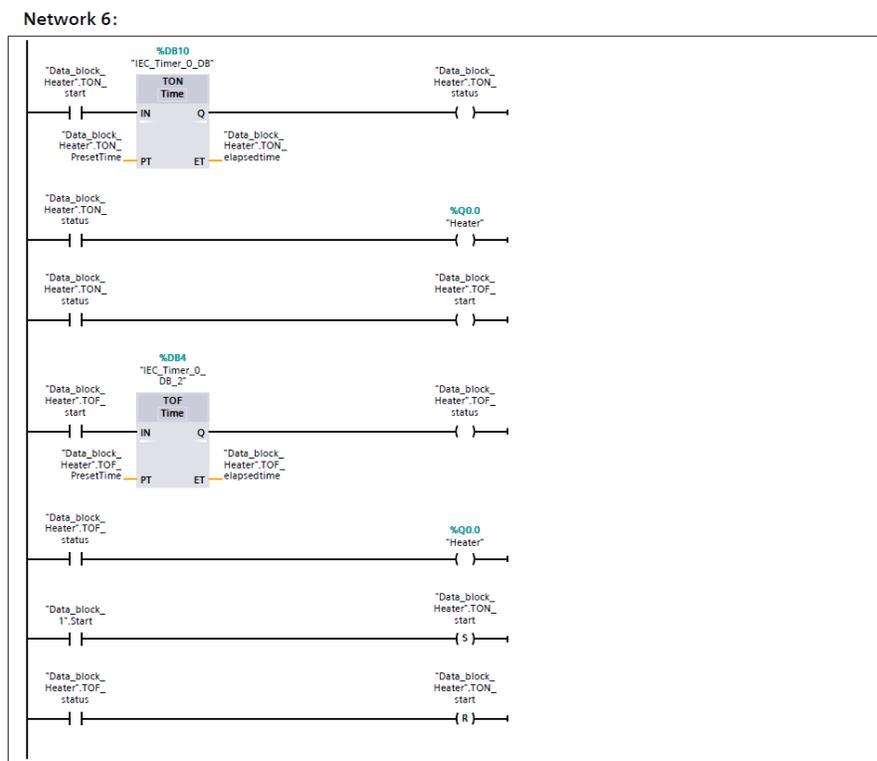


Figure 4.7: PLC Code

“TON” timer sets output to ON after a preset time delay. “TOF” timer resets output to OFF after a preset time delay.

4.2.1 IR Lamp Transfer Function

In order to obtain a mathematical description of the IR Lamp, a Ziegler-Nichols method design approach was completed. Known as the process reaction method, it requires the open-loop step response of the process to be recorded and is a practical means of acquiring the transfer function of the IR heater.

The S-shaped curve is made by two constants, delay time L and time constant T . By drawing a tangent line at the inflexion point of the S-shaped curve and determining the intersections of the tangent line with the time axis and the line $c(t) = K$, the values for the delay time and time constant are determined. The transfer function $G_p(s) = C(s)/U(s)$ is approximated by a first-order system with a transport lag [22]:

$$G_p(s) = \frac{C(s)}{U(s)} = \frac{K e^{-Ls}}{Ts+1} \quad (\text{Equ.4.1})$$

Collecting data of time and temperature measurement, the open loop step response of the IR heater under test resulted in the curve shown in the figure below.

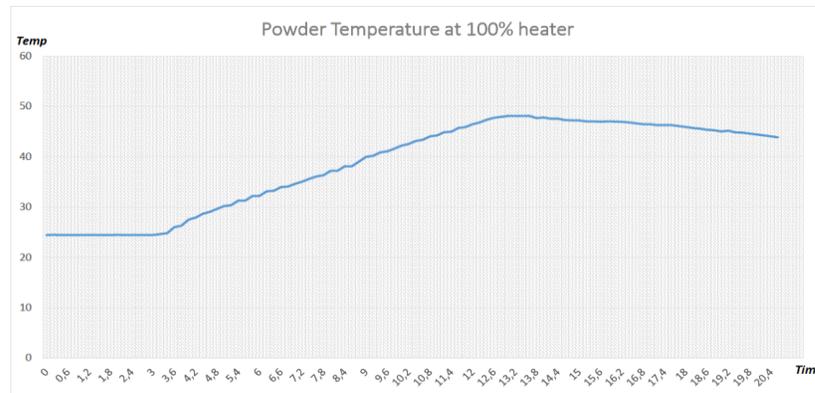


Figure 4.8: Temperature measurement with IR lamp ON at 100%

Using the Ziegler-Nichols process reaction method, the plant (infrared lamp) was found to have: $K = 0.8$, $L = 0.5$, $T = 4.6$

In order to verify the validity of test, a simulation using MATLAB was performed. This resulted in the curve in figure 4.8, which is a close approximation of figure 4.9.

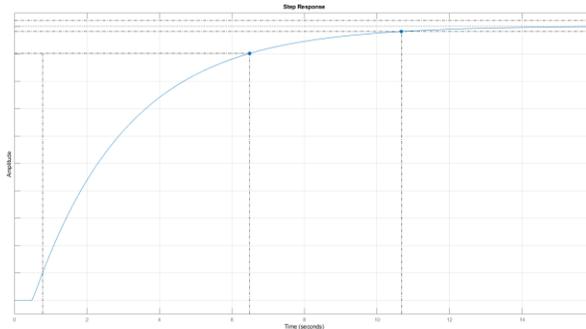


Figure 4.9: Matlab Simulation of IR lamp transfer function

Matlab simulation confirms trajectory fairly accurate and the final transfer function can be expressed as:

$$G_p(s) = \frac{C(s)}{U(s)} = \frac{0.8 e^{-0.5 s}}{4.6 s + 1} \quad (\text{Equ.4.2})$$

The mathematical transfer function allow to compute the PID control in Matlab and compare the Matlab /Simulink simulation results with the test results by using the PID_compact in Simatic S7-1200.

By using Simulink, perform a simulation of the control system is possible, computing the PID parameters thanks to the block “PID 2DOF” that implement the same algorithm used from PID_Compact in Tia Portal:



Figure 4.10: Simulink PID control system

4.2.2 Current and Power Measurements

A disadvantage of using IR lamp is the huge amount of current and power that it requires. For this reason a test measuring current and power used from the lamp is useful to get information for overall safety of the machine and to estimate the apparent and active power. Tests showed the following results:

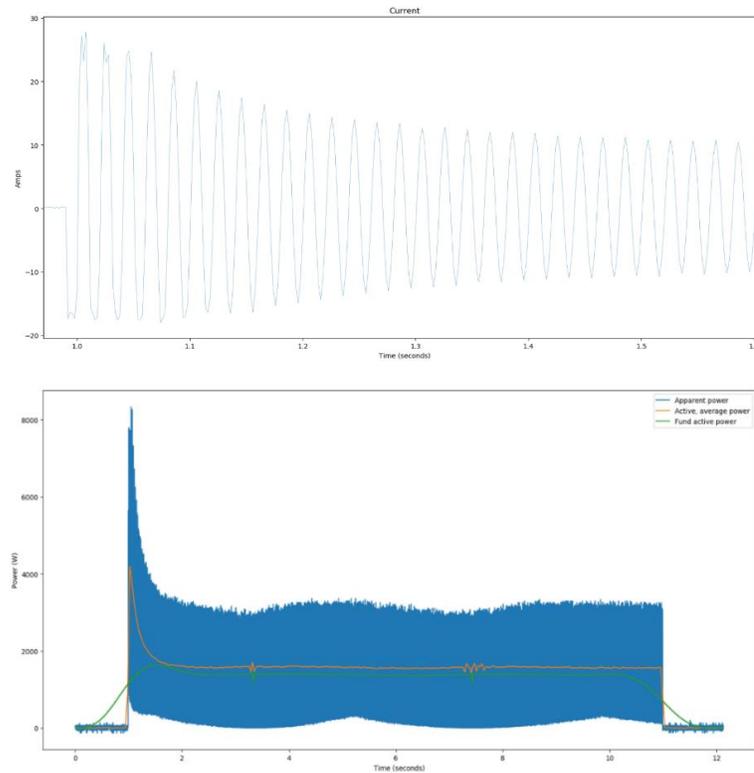


Figure 4.11: Power Measurements

The nominal current used is around 12 A, even if there is an inrush current of 25 A in the initial time, for 200 ms. The system is single-phase 230 Vac. Blue curve represents the apparent power that is the maximum power that can be accommodate by the supplying equipment while the thermal stress on conductors' insulation remains the same, and it is defined as $S = V I$. Green curve is the active power, in single-phase systems generally defined as $P = V I \cos(\Theta)$, that is the power used from the lamp. Test was done turning on only the lamp and the active power results around 1.5 kW, as planned.

4.3 Temperature Control (Static) Test

After testing lamp and sensor, a temperature control test is implemented by using the PID_compact block in Tia Portal, performing different tests to reach a good solution in terms of settling time, rise time and overshoot. Tests are performed in a simulate design assembling sensor and IR lamp covered with a metal, to not influence the temperature measurement.

Simulation model tries to represent the behavior of the system in a physical domain of interest and it will allow to:

- Get a mathematical model of IR lamp, as explained in the 4.2.1 chapter.
- Get information of how change the behavior of the system depending on preformed P, PI, PD or PID control
- Data from PWM output and zero cross for AC power control
- Test the correct behavior of the system
- Improve the system
- Avoid future errors

Time Response Requirements

In order to reach a good optimization of the system, in static condition, the time response requirements in terms of rise time, settling time and overshoot are:

RiseTime	<	6s
SettlingTime _{5%}	<	8s
Overshoot	<	5%

Therefore, IR lamp must be able to heat up the temperature of the powder in its set-point in less than 6 seconds with a temperature peak that must to not overcome 5% of overshoot.

4.3.1 PID Compact - PLC Code

Temperature control is performed thanks to PID_compact technologic object in Tia Portal. The code implemented is:

Network 6: Initial call of this OB



Figure 4.12: PLC Code

IW64 and Q0.8 are the defined variable in PLC tags and respectively they are analog input for IR sensor and digital output for IR Lamp.

When “Data_block_1_start” is True, it activates “PID_Compact”.

“Data_block_1_start” can be set in the watch table.

The actual program (the call of the “PID_Compact” compact controller) takes place in a *cyclic interrupt* OB, since discrete software controls must be called in a defined time interval for optimizing the controller quality.

100 ms were set as a constant time interval for the scan time of OB200.

Start Value Control (Config)

InputPerOn	=	True
LowerPointIn	=	5530.0
UpperPointIn	=	27648.0
InputLowerLimit	=	-20.0
InputUpperLimit	=	100.0
OutputLowerLimit	=	0.0
OutputUpperLimit	=	100.0
SubstituteOutput	=	0.0

4.3.2 Pre-tuning and Fine-Tuning

The initial commissioning of a plant usually starts by carrying out a pre-tuning to perform a first setting of the PID parameters and to control the operating point. For tuning different choices are possible, defining tuning methods in PidSelfTune.TIR.TuneRule:

- PID automatic
- PID fast
- PID slow
- Ziegler-Nichols PID
- Ziegler-Nichols PI
- Ziegler-Nichols P

During testing, a Ziegler-Nichols PI is chosen.

Settings:

```
Static.RunModeByStartUp = True  
InOut.Mode = 1 (for Pre Tuning)  
InOut.Mode = 2 (for Fine Tuning)  
PidSelfTune.TIR.TuneRule = 4 (Ziegler-Nichols PI rule for tuning)  
Input.ManualValue = False  
Input.Reset = False
```

Procedure:

- Start the measurements choosing the sampling time of data acquisition.
- The tuning status indicates that tuning has not yet been started and after the first startup of the CPU the controller is in “Disabled - Inactive” mode
- Perform a pre-tuning process, entering a set-point ideally in the central area of the actual range
- If pre-tuning mode is performed without errors the PID parameters have been tuned right
- After successful pre-tuning, the controller goes to automatic mode. The determined values can be viewed via “Go to PID parameters”

- Selecting “Upload PID parameters” it will write the determined values as start values. They can be viewed in the “Parameters View” in Configuration panel
- To obtain the best parameter performing fine tuning can improve the PID parameters
- Start the fine tuning process and repeat the same process
- After successfully terminating the fine tuning uploads the new PID parameters as start values to the instance data block of “PID_Compact”.

The determined controller parameters, after fine tuning, are located in the `Retain.CtrlParams` structure and the controller parameters prior to tuning are moved to `Retain.CtrlParamsBackUp`. In order to use these parameters they must be written to the instance of `PID_compact` as start values.

Retain.CtrlParams

<i>Gain</i>	=	15.98
<i>Ti</i>	=	4.938
<i>Td</i>	=	0
<i>TdFlntRatio</i>	=	0.1
<i>PWeighting</i>	=	0.8
<i>DWeighting</i>	=	0
<i>Cycle</i>	=	0.05

It results in a PI controller according. The cycle time represents the cycle time of the PID algorithm.

Computing the PID control of the dynamic system with this parameter, the time response is:

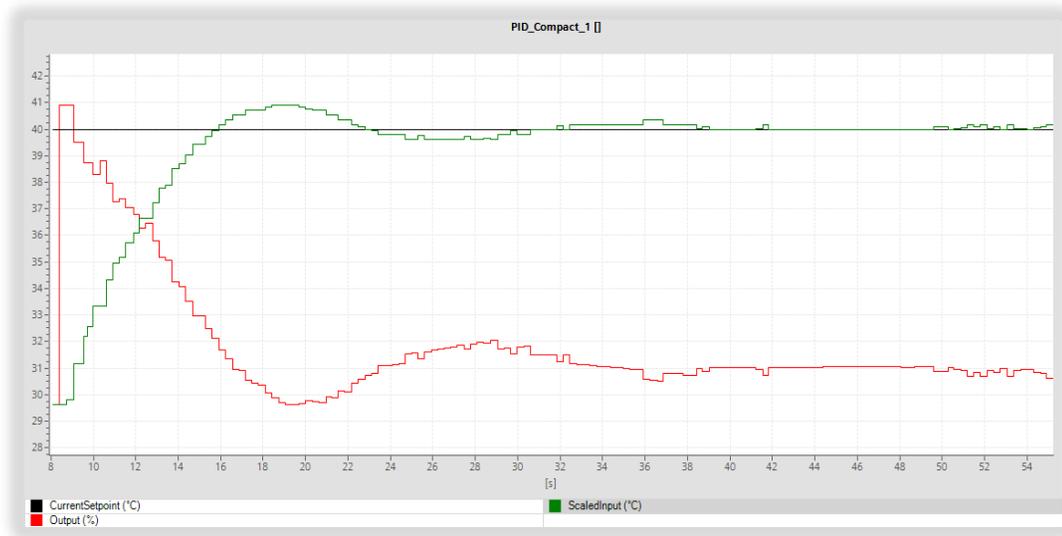


Figure 4.13: System response of PI temperature control with 40°C setpoint in fine tuning mode

The green curve is the temperature of the print-bed, output of control system, and the red curve is the PWM output of the controller (input for IR Lamp).

Analyzing step-response characteristics in terms of rise time, settling time, and overshoot:

Set-point	=	40°C
Initial Temperature	=	29.62
Peak	=	40.94°C
RiseTime	=	6.58s
SettlingTime _{5%}	=	20.58s
Overshoot%	=	9.76%

Time response requirements are not satisfied with the pre-tuning and fine-tuning mode, and there is a little oscillation not desired. This test is useful to have an idea to how the system behaves and the range of PID parameters. In the following section, thanks to the automatic mode where it is possible to change the PID parameters several tests are computed to reach a good optimization of the control

4.3.3 Automatic Mode

Automatic mode (the standard PID control mode) allows to change PID parameters. In this section, different tests are performed to improve the control system. The result of the PID algorithm determines the output values. PID_Compact switches to inactive if an error occurs and “ActivateRecoverMode” = FALSE.

To change PID parameters online, go into CtrlParamsBackUp structure and apply Retain.CtrlParams.LoadBackUp = True. Online change in Automatic Mode can result in a jumps at the output value. It is suggested to change the currently PID parameters only in “Inactive” mode online to prevent malfunction of PID controller.

Settings:

Static.RunModeByStartUp	= True
InOut.Mode	= 3
Input.ManualValue	= False
Input.Reset	= False
Static.ActivateRecoverMode	= False
Retain.CtrlParamsBackUp	= True
Retain.CtrlParams.LoadBackUp	= False

1) First Test: PI control

In this test, starting from the results from fine tuning PID parameters are changed to improve time response of system. Increasing the proportional coefficient allow to make the action of the system more sensitive, faster and steady-state error reduced. If K (*Gain*) is too large, the system will tend to be unstable and if K is too small, the system will suffer from slow movements. Integral action undermines the system’s stability. Small T_i (strong integral action) will lead to unstable system, but it could remove the stable state error and improves the control accuracy of the system.

During this test, proportional gain is increased a bit and integral action decreased in order to get a faster time response and improve steady state avoiding oscillations. PID parameters are modified as follow:

Retain.CtrlParams

Gain = 17.32
Ti = 3.28
Td = 0
TdFlntRatio = 0.1
PWeighting = 0.8
DWeighting = 0
Cycle = 0.05

PI algorithm of controller becomes:

$$G_C = 17.32 \left[(0.8 w - x) + \frac{1}{3.28 s} (w - x) \right] \quad (\text{Equ.4.3})$$

Having a set-point (w) of 40°C, step response of control system is:

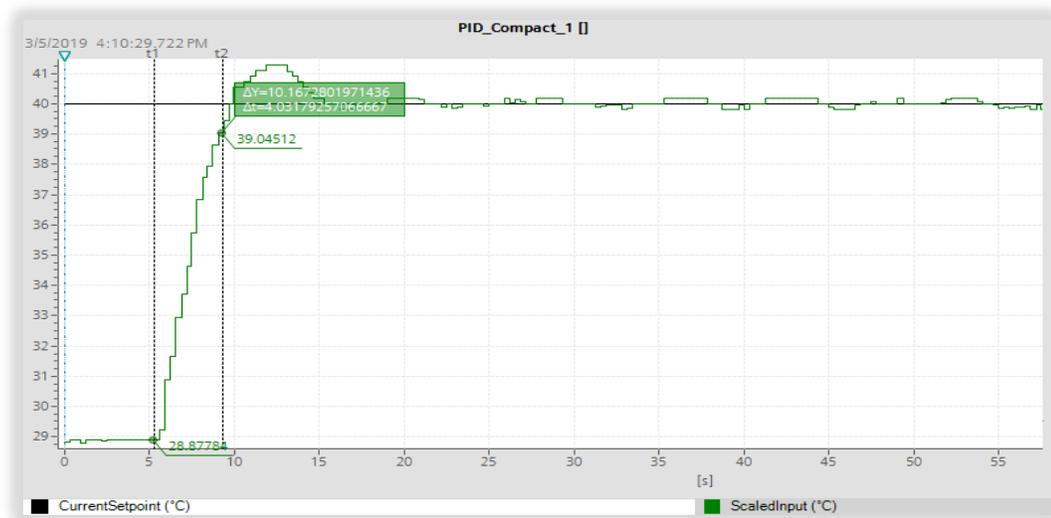


Figure 4.14: System response of PI temperature control with 40°C setpoint in automatic mode

Set-point	=	40°C
Initial Temperature	=	28.87
Peak	=	41.34°C
RiseTime	=	4.03s
SettlingTime _{5%}	=	9.89s
Overshoot%	=	14.91%

Rise Time and Settling time are less than in the fine tuning test, but the overshoot is higher with a peak of 41.34°C.

2) Second Test: PID control

A PID controller allows to reduce peak and overshoot of control system, Differential action could improve the dynamic features. When TD becomes relatively large, it has large overshoot and short adjustment time. When TD becomes relatively small, it also has large overshoot but long adjustment time. Only TD proper could reduce overshoot and adjustment time. After some tests a proper Td parameter is found to be:

Retain.CtrlParams

<i>Gain</i>	=	17.32
<i>Ti</i>	=	3.28
<i>Td</i>	=	0.72
<i>TdFlntRatio</i>	=	0.1
<i>PWeighting</i>	=	0.8
<i>DWeighting</i>	=	0
<i>Cycle</i>	=	0.05

PID algorithm of controller operates according to the following equation:

$$G_C = 17.32 \left[(0.8 w - x) + \frac{1}{3.28 s} (w - x) + \frac{0.72 s}{0.72 * 0.1 s + 1} (-x) \right] \quad (\text{Equ.4.4})$$

The PID control system gave following result:

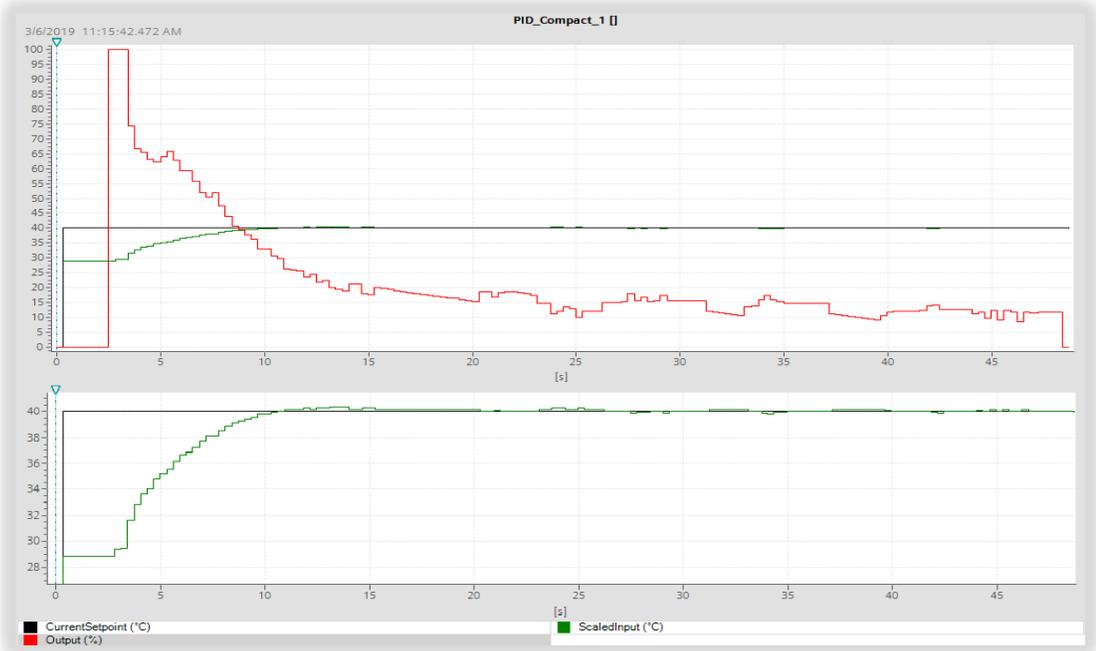


Figure 4.15: System response of PID temperature control with 40°C set-point in automatic mode

Set-point	=	40°C
Initial Temperature	=	29.07
Peak	=	40.18°C
RiseTime	=	5.73s
SettlingTime _{5%}	=	7.19s
Overshoot%	=	1.96%

Figure 4.15 shows temperature of powder (green curve) and percentage of PWM output of controller (red curve). Overshoot and peak temperature are decreased thanks to the derivative action, with a slightly increasing of rise time and settling time but they fulfill time response requirements with a good improvement of previous controls.

5. Testing on printer

Tests on simulate design are useful to check reliability of the system, validating and verifying working of sensor and the overall PID control of IR lamp. In this section the complete integrated system is assembled considering the system design and the assumption made in chapter 3 and 4 and temperature control of pint-bed is tested on printer to evaluate the system's compliance with its specified requirements, implementing PLC code of PID_Compact.

5.1 PLC Code

Y axis is moved by using MC_MoveAbsolute block in Tia Portal Simatic s7-1200.

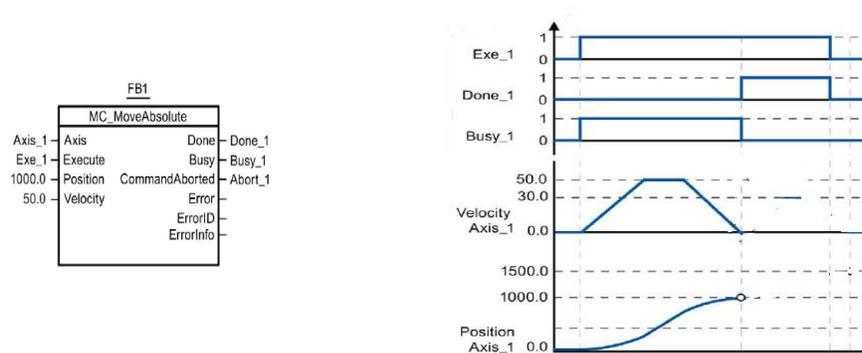


Figure 5.1: MoveAbsolute instructions

MC_MoveAbsolute let the axis move toward the position entered, so it keeps track of the home point and the current position of the axis:

- “Axis”: it is the axis technology object to move
- “Execute”: the task starts with a positive edge.
- “Busy”: the task is being executed when is True
- “Done”: it is True when absolute target position is reached
- “Position”: it is the absolute target position

- “Velocity”: it is the velocity of axis according with profile

Axis first must be homed.

PLC code for movement of Y axis is:

Network 4:

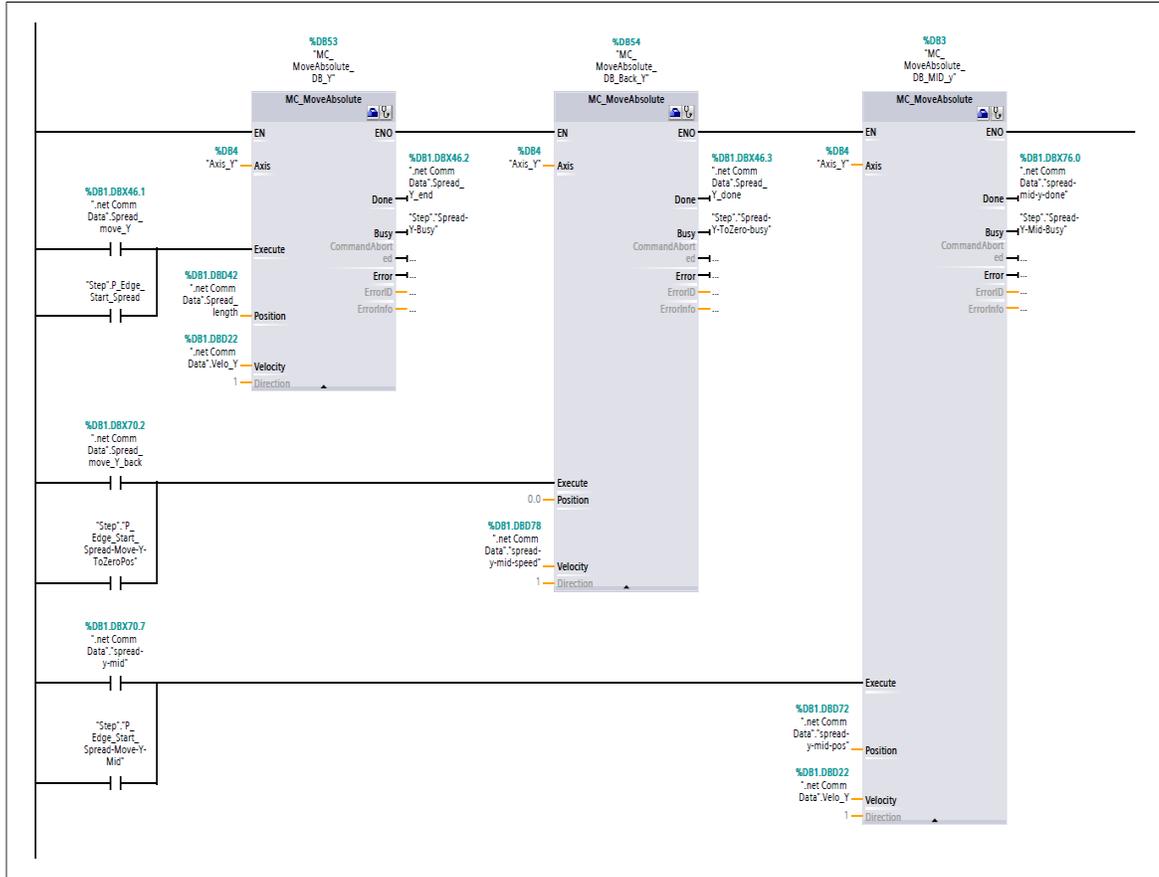


Figure 5.2: PLC Code

- *MC_MoveAbsolute_DB_Y* block moves axis from last position during printing to 700.0 mm position
- *MC_MoveAbsolute_MD_Y* moves y axis from 700.0 to 400.0 position
- *MC_MoveAbsolute_DB_BACK_Y* moves y axis from 400.0 to 0.0 position with a spread-y-mid-speed equal to 40.0 mm/s

Spreader and roller are activated when “done” command of MC_MoveAbsolute_DB_Y is True

➤ *spread_y_end* = *True*

IR lamp and temperature control must be activated during “execute” or “busy” command of *MC_MoveAbsolute_DB_BACK_Y*:

- *spread-mid-y-done* = *True*
- OR
- *Spread-Y-toZero-busy* = *True*

A positive edge as output (“*Step*”.*P_Edge_Start_Spread-Move-Y.ToZeroPos*”) is used to assign bit True when a positive transition (Off to On) is detected on the power flow entering the coil; the power flow state always passes through the coil as the power glow entering the coil. P coil can be located anywhere in the network.

When *spread-mid-y-done* or *Spread-Y-toZero-busy* is True (it means during spreading operation y axis is in 400.0 position) positive edge is detected and IR lamp and temperature control must be activated:

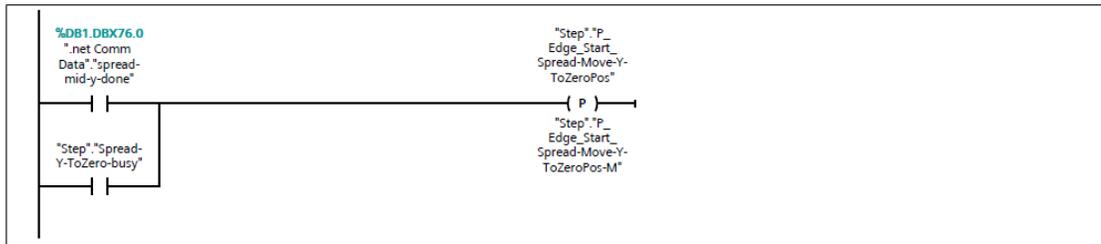


Figure 5.3: PLC Code

To activate or deactivate IR lamp, two different variables are used in order to control the status of lamp:

- *Heater_start*
- *Heater_stop*

Their start value is False.

Heater_start is True when the positive edge “Step”.P_Edge_Start_Spread-Move-Y.ToZeroPos is detected AND *Heater_stop* is negate. *Heater_start* remains ON due to *Heater_start* on input, necessary code for continuous operations:

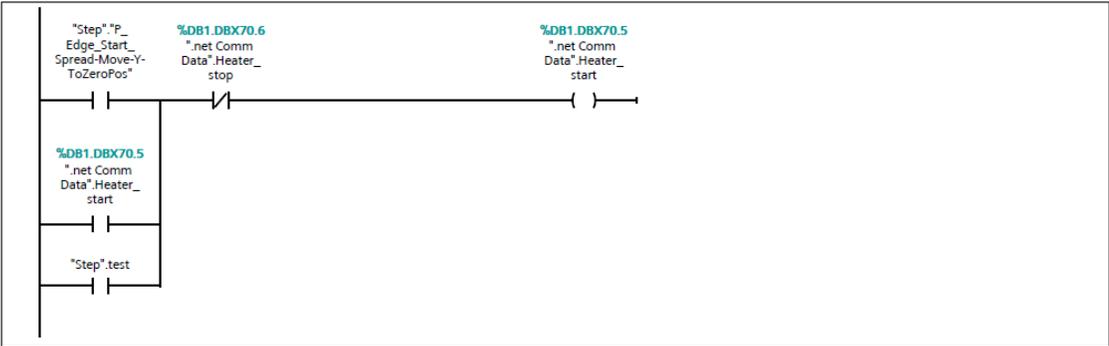


Figure 5.4: PLC Code

For *Heater_stop* a set-reset instruction is used. When S (set) output is activated, then the data value at the OUT address is set to 1; when R (reset) is activated, then the data value at the output address is set to 0; when S is not activated, output is not changed. In this case *Heater_stop* output is set to 1 when positive edge of spread-Y-done is true, it means when y axis reaches 0.0 position and IR lamp must be turned OFF and due to the previous code in figure 5.4 *Heater_Start* will be False. *Heater_stop* is reset at his start value after *Spread-Y-done*

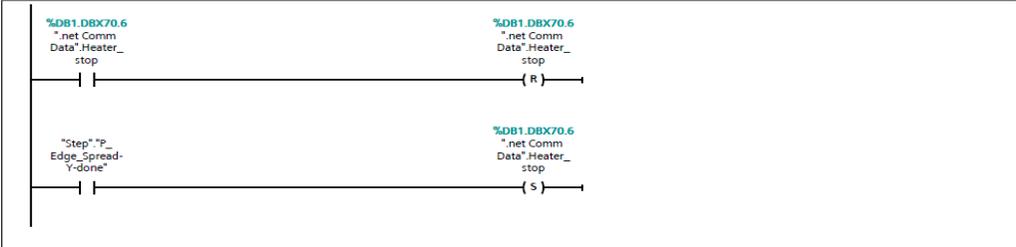


Figure 5.5: PLC Code

PID_Compact is called in a cycling interrupt with a 100 ms constant time interval for the scan time of OB. Controller is enabled through *Heater_start* when it is true. *Reset* is used to restarts the controller. From False to True edge it switches

to “inactive” mode, maintaining PID parameters. As long as *Reset* = True, PID_Compact remains in “inactive” mode (*State* = 0). From True to False edge, PID_compact switches to operating mode that is saved in the *Mode* parameter. To do that negate Heater_start is used. The controller must be reset, otherwise there could be some errors in computing the PID algorithm because when the controller is not enabled the last temperature measured from the sensor will be the first temperature input in the next cycle of heating ‘new’ printed layer. ”Enable” of PID_Compact needs a timer off (TOF) of a small time otherwise the reset is not worked properly.

Network 2: pulse width modulated output value

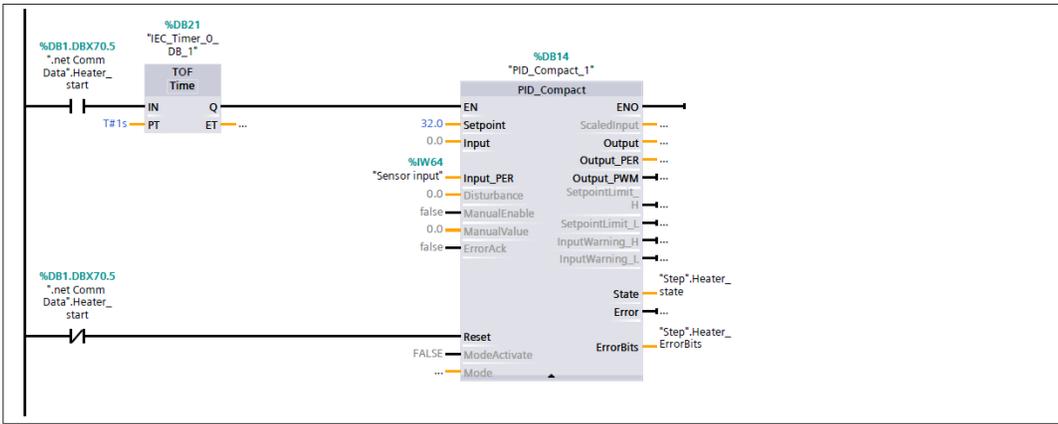


Figure 5.6: PID_Compact PLC Code

Digital output of the Relay of IR Lamp is Q8.3 and it is called in the main program and it is ON when *Heater_Start* is True and *PID_Compact_1_Output_PWM* gives the output of PID_Compact

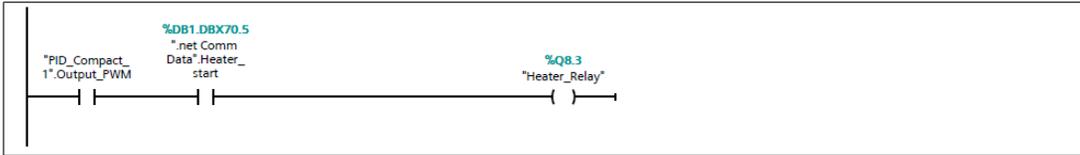


Figure 5.7: PLC Code

Summarizing, the figure below shows how the step response of control system will appear during the entire process:

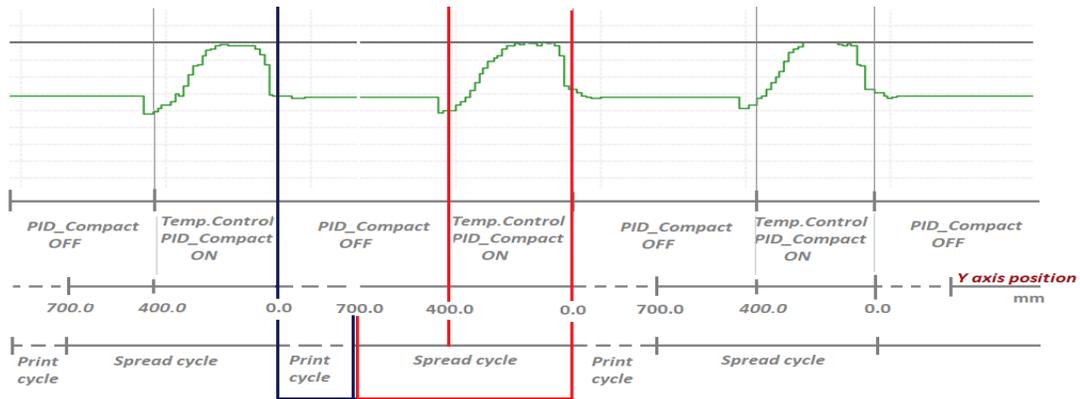


Figure 5.8: System Response of PID_Compact during entire process

Printing and spreading process:

1. Print cycle starts, y axis is in the printing side, x axis is moving, inkjet is active and the binder meets the powder
2. Finish of printing the layer, Y axis goes to 700.0 mm position
3. Z1 is moved up
4. Y axis goes from 700.0 to 400.0 mm position with a velocity of 100 mm/s, and the roller is displacing the powder for “new” layer.
5. Z2 axis goes down
6. Y axis goes from 400.0 to 0.0 mm position with a velocity of 40.0 mm/s, the roller is spreading the “new” layer and temperature control of print-bed is active (PID_Compact enabled)
7. When Y axis reaches 0.0 mm position, spreading process finishes, roller is turned off, IR lamp is turned off and temperature control is not active anymore (PID_compact disabled)
8. Y axis goes in the middle of print bed and a new printing process starts

Important to notice that PID_Compact is enabled only on step 6.

5.2 System Response

The goal is to get controller able to control temperature of printed layer for different set-points, checking how system reacts to a sudden change in PID parameters.

General starting values:

<i>Static.RunModeByStartUp</i>	=	<i>True</i>
<i>InOut.Mode</i>	=	<i>3</i>
<i>Input.ManualValue</i>	=	<i>False</i>
<i>Static.ActivateRecoverMode</i>	=	<i>False</i>
<i>Retain.CtrlParamsBackUp</i>	=	<i>True</i>
<i>Retain.CtrlParams.LoadBackUp</i>	=	<i>False</i>

5.2.1 First Test

First test is performed by using PID parameters found in the static test in automatic mode

Retain.CtrlParams

<i>Gain</i>	=	17.32
<i>Ti</i>	=	3.28
<i>Td</i>	=	0.72
<i>TdFlntRatio</i>	=	0.1
<i>PWeighting</i>	=	0.8
<i>DWeighting</i>	=	0
<i>Cycle</i>	=	0.05

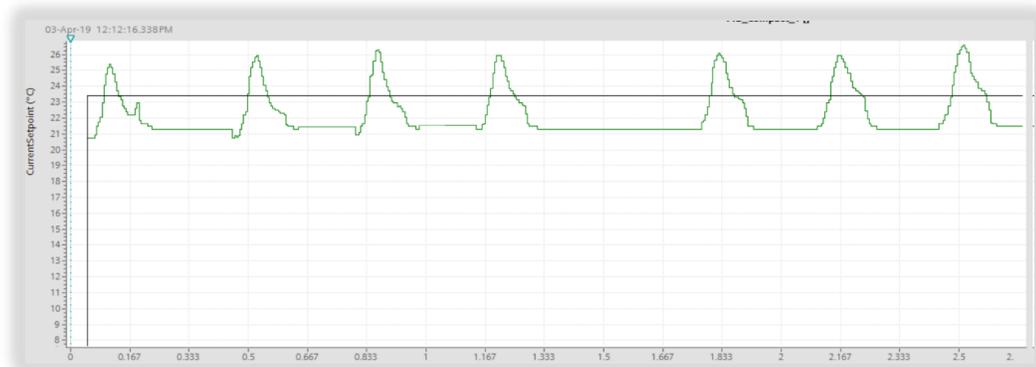


Figure 5.9: Test 1 - System response of PID control tested during spreading process on print-bed

System responses with a huge temperature peak in the first part of print-bed then the lamp reduces its power and printing bed is not heated uniformly.

5.2.2 Second Test

PID parameters are modified in order to get a system steady state stable and to have a uniform heating of printing bed. Peak can be reduced decreasing the gain and delaying the integral action, increasing it; derivative action parameter is also a bit increased.

Retain.CtrlParams

- Gain* = 1.56
- Ti* = 8.62
- Td* = 0.92
- TdFlntRatio* = 0.1
- PWeighting* = 0.8
- DWeighting* = 0
- Cycle* = 0.05

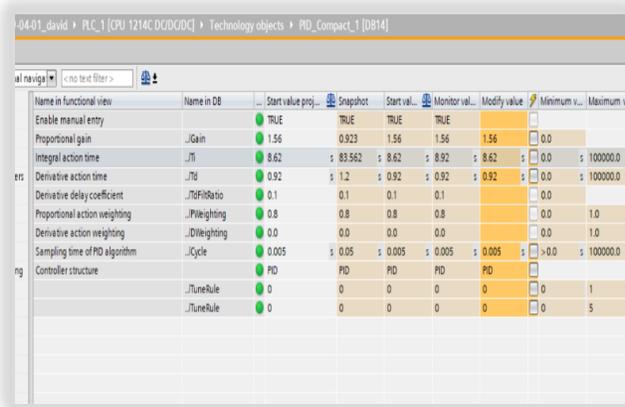


Figure 5.10: PID parameters in a Function View on Tia Portal

System response with modified PID parameters is:

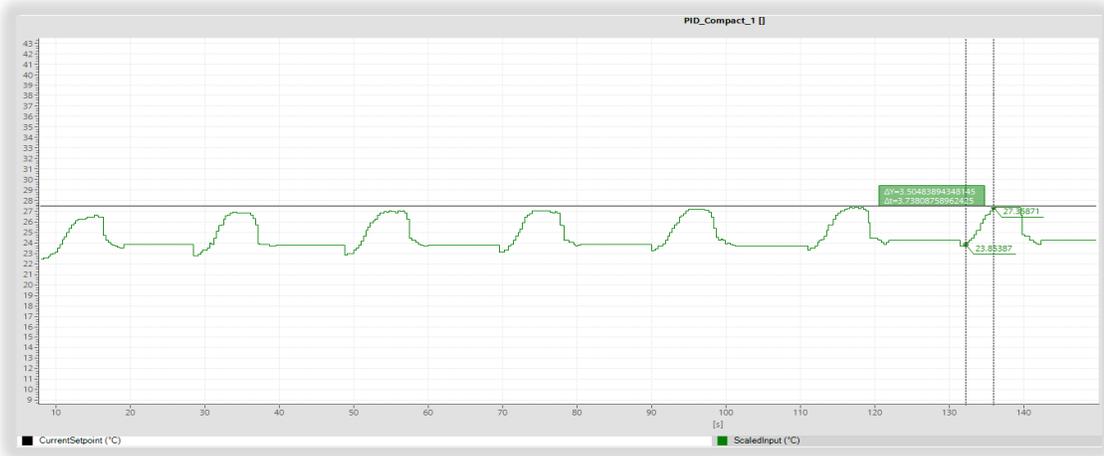


Figure 5.11: Test 2 - System response of PID control tested during spreading process on print-bed

Set-point	=	27.5°C
Initial Temperature	=	22.4°C
Peak	=	27.5°C
RiseTime	=	3.05s
SettlingTime _{5%}	=	3.42s
Overshoot%	=	0%

Set PID_parameters allow to reach a good control of printing part. Set-point is reached after 3-4 cycle. The system reaches 95% of temperature after 3.5 seconds (in the third cycle) and it can follow the reference for 6.5 seconds, steady-stable stable. After each cycle initial temperature is different because the heat is transferred between the layers.

5.2.3 Final Results

Concr3de is interested to heat up different mixture, setting different set-point depending on the application, between 25°C and 35°C at most. For this reason some tests are performed with different set-points. During a printing process, control must be continue and it must give the same temperature on each printed layer.

- Set-point = 28°C

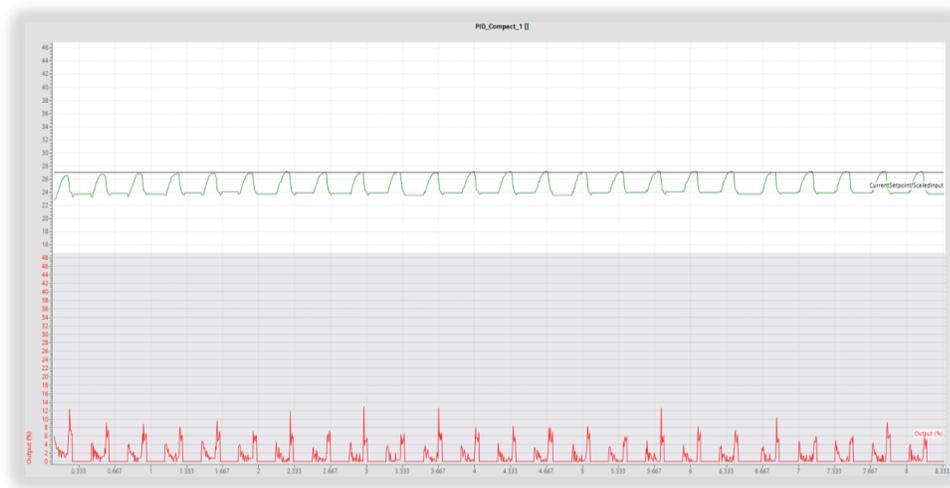


Figure 5.12: Test 3 – System response of PID control tested during spreading process on print-bed

PID_Compact allow to control the temperature of print-bed. IR lamp is able to heat up the temperature of layer at 28°C for each layer. PWM output is between 5% - 15%, in a 50 ms sampling time of PID algorithm.

- Set-point = 32°C



Figure 5.13: Test 4 - System response of PID control tested during spreading process on print-bed

In this case IR lamp works up to 36% of PWM to reach a 32°C set-point in each cycle, with same PID parameters. Set-point is reached after 6-7 spread cycles.

Conclusion

The PID control gave good results let to control temperature of print-bed during the entire process of printing. The PWM output, so the intensity and power of infrared lamp is gradually reduced because of the heat power transmission that a pre-heated layer gives to the new one, being each layer around $2/3 \mu\text{m}$.

The system was tested on Mino-Rhino and it will be part of Armadillo black and Armadillo white that are still in development phase. It is a first approach to temperature control of print-bed and it will be improved testing it on Armadillo printer.

Not every kind of powders need to have an increase of temperature, some materials have negative effects so there will be a possibility in Noah software to choose if activate or deactivate the temperature control, let to choose to user what he wants to do.

A disadvantage can represent an increasing of temperature in the chamber of printer and the external environment after some hours of printing, due to the reflected heat from the surface. An approach to control also the temperature of inner environment was investigated adding a cooler, but it will introduce an air flux in the working platform of printer that can affect the printing precision due to the micro movements of powder on print-bed.

The response of system strongly depends on the power and time response of heater lamp during turn on and turn off. A metal cover must be properly designed to concentrate all the heated power on surface avoiding that the reflected power can affect the measurement of sensor and overheating parts near the lamp. In the next design a different lamp is suggested to use which can guarantee a fast response and a major coefficient of absorption by properly choosing the wavelength of radiation and by using a reflector on the quartz tube to better focus all the energy emitted on the material.

There still are not enough data to say if the increasing of temperature improved the compress strength of printed object but temperature control of print-bed represents a possibility that allows to test, change and obtain different physical and chemical properties of product. This is an important fact for Concr3de that wants to give to architects, creators, designers, product companies and researchers all the freedom to improve material properties.

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