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ÓBUDA UNIVERSITY

KANDÓ KÁLMÁN FACULTY OF ELECTRICAL ENGINEERING
ELECTRONIC AND COMMUNICATION SYSTEMS INSTITUTE
INSTRUMENTATION AND AUTOMATION DEPARTMENT

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THESIS ASSIGNMENT

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Branch of study:
Specialization: Instrumentation and automation specialisation

Thesis title: Measurement and control of coolant composition of cutting machines using PLC
Task description: Quality control and, if necessary, automated maintenance of the coolant of cutting machines in a cutting plant.
Tasks to be performed::
- pH measurement to measure the accumulation of organic substances
- measurement of the oil content of coolant using a refractometer
- in the case of foaming, addition of antifoaming agent

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STUDENT STATEMENT

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Contents

1 Introduction

The objective of this project is to automate the quality control process for the cooling lubricant used in a CNC machine. The connected cooling system consists of two separate tanks and a cleaning loop. Once the coolant exits the machine, it initially enters a buffer tank known as the 'dirty tank,' undergoes cleaning through a dedicated loop, and is subsequently stored in a 'clean tank.'
Maintaining the oil percentage in the emulsion within a specified range is crucial for coolant quality. Inappropriate concentration of the emulsion can lead to inadequate cooling properties, which then can cause unrepairable damage to the cutting edge of the CNC machine. Over time, the oil content increases due to water evaporation, necessitating constant monitoring and frequent refilling to meet specifications. Previously a manual process, daily measurements of emulsion oil content were taken, and the required amount of emulsion was added accordingly.
The second critical aspect of coolant quality is the level of organic matter in the emulsion. Currently, this is monitored through biweekly sampling and testing, which cannot be cost-effectively automated. However, the frequency of testing can be reduced by continuously monitoring the solution and conducting tests only when necessary. Changes in pH levels, resulting from the accumulation of organic matter, can serve as an early warning for further testing required.
Another project goal is to address foaming in the 'dirty tank.' In the manual process before automation, operators applied anti-foaming agent to the emulsion at their discretion, often leading to spillovers due to negligence. The aim is to automate this process and mitigate the occurrence of such incidents.

2 Parameters to be measured

For this control process to be achieved certain properties of the cooling lubricant have to be constantly measured and monitored.

2.1 Level measurement

Fluid level measurement is crucial to this project. Level measurement in the 'clean tank' is required for the calculation of additional emulsion needed to stay within the specified range of concentration. This measurement is also necessary to prevent any chance of overfilling the tank which would lead to catastrophic failures causing material damage and the interruption of production.

Level measurement in the barrel is also necessary to stop the pump from running dry, thus causing irreparable damage to the machine. The other motivation for this measurement is to providing the necessary information to the personnel responsible for the maintenance of the cooling loop when the barrel has to be replaced with a fresh one.

2.2 Concentration measurement

Concentration measurement of the emulsion inside the 'clean tank' is needed to monitor and to control the quality of the cooling lubricant. This measured value is later used to determine the amount of additional emulsion to be transferred into the tank.

2.3 Organic matter measurement

Organic matter measurement is made necessary because of the potential negative health effects of the build-up of organic matters inside the emulsion. This measurement is only to monitor the changes in the amount of organic matter inside the cooling lubricant, and is used to alert the maintenance personnel of further testing and intervention required.

3 CNC machines

In the world of manufacturing, CNC, or ”computer numerical control,” machines represent a revolutionary approach to managing complex tasks efficiently. This innovative technology finds widespread applications, particularly in the metal and plastic production sectors.

CNC machining:

CNC machining is a sophisticated manufacturing process where computer software takes the lead in directing the movement of factory tools and machinery. This process is prominently employed in achieving three-dimensional cutting tasks with minimal human intervention. CNC machines operate autonomously once programmed, functioning akin to robots. The programming involves specifying the speed and position of machinery and tools, enabling precise execution of tasks. CNC Machines vs. NCM Machines: Distinguishing CNC from NCM (”numerical control machine”), CNC programming involves feeding programs into computers through small keyboards, a departure from the use of computer punch cards in NCM machines. The retained programming in the computer memory, coupled with human programmers, enhances computational capacity, allowing for more extensive and flexible CNC programming.

Open loop machines vs. Closed loop machines:

The majority of CNC machines operate in a closed-loop system, minimizing the risk of errors and promptly addressing irregularities. In contrast, open-loop machines run in a single line from control to motor, allowing for potential irregularities due to the one-way dictation.

CNC programming:

A Deep Dive: CNC machining heavily relies on programming, with human programmers inputting codes to ensure proper functionality. The language of CNC machining, known as G-Code, is intricate, controlling various behaviors such as speed, feed rate, and coordination within CNC machines. Programming CNC machines involves a step-by-step process, starting with the conception of a two- or three-dimensional computer-aided drawing of the desired end product. This drawing is then translated into computer code for the CNC system to interpret. The machine operator conducts trial runs to identify and rectify any coding errors before finalizing the process.

Errors in CNC machining:

While CNC machining is a remarkable technology, it is not without imperfections. One significant challenge lies in the computer's assumption of perfection, often overlooking the potential for errors. These errors become more likely in situations where a machine is coded to cut in multiple directions simultaneously.

Applications and evolution of CNC machines:

CNC machines have evolved from the numerical control technology of the 1940s, where motors controlled tool movement. The integration of digital computer technology in the modern era has propelled CNC machining to new heights, simplifying operations across various industries. CNC machines are versatile, accommodating a wide range of materials such as metal, glass, plastic, wood, foam, and composites. Their applications span from manufacturing clothing to crafting intricate aerospace components.

Types of CNC machines:

While the fundamental principle of CNC machines remains consistent, their specific functions vary across different types. Some prominent examples include:

- CNC Mills: Utilized for various cutting tasks, with newer models operating on a sophisticated six-axis system.
- Lathes: Specialized in cutting circular designs with precision, often employed for complex designs with a two-axis system.
- Plasma Cutters: Ideal for precision cuts in metal, utilizing compressed-air gas and electrical arches for efficiency.
- Wire Electric Discharge Machines (Wire EDMs): Employing electrical sparks for molding pieces, particularly effective on electronically conductive materials.
- Sinker Electric Discharge Machines (Sinker EDMs): Operating similarly to wire EDMs, but utilizing a dielectric fluid to conduct electricity for shaping pieces.
- Water Jet Cutters: Employing high-pressure water for cutting hard materials, often mixed with abrasives like sand for enhanced cutting power.
- CNC Drilling Machines: Utilizing multi-point drill bits to create circular holes in workpieces, with the flexibility to create both vertical and angular holes.

3.1 Coolants

In the intricate world of machining operations, effectively managing heat energy stands as a critical necessity. The ramifications of excessive heat in cutting processes on tools and workpieces underscore the need for meticulous control measures, striking a delicate balance between preserving product quality and enhancing productivity. Coolants, synonymous with cutting fluids, emerge as indispensable contributors, significantly influencing the outcome of metal cutting processes, especially in the realm of CNC machining.

Understanding Coolant:

Coolant, or cutting fluid, represents an industrial elixir meticulously crafted to cool and lubricate cutting tools and workpieces during metal cutting endeavors. Infused with an array of functional additives within a fluid composition, it typically encompasses elements like petroleum distillate, animal fat, vegetable oil, water, or other raw materials. Distinct from conventional soap-based emulsions, modern cutting fluids excel in cooling performance, ensuring suitability for the cutting and grinding of ferrous metals. Their attributes include non-toxicity, absence of odor, and environmental friendliness, posing no adverse effects on machinery or the workshop environment.

Application:

Cooling and Lubrication The dual roles of cooling and lubrication define the pivotal function of coolants in machining operations. The heat generated during the machining process, a consequence of the tool and workpiece friction, necessitates the adoption of liquid coolants for sustained, heavy cutting operations. Their ability to dissipate heat rapidly facilitates quicker cutting speeds, reduces friction, and minimizes tool wear.
Lubrication, occurring at the tool and workpiece interface, plays a crucial role in preventing chip welding, aiding chip evacuation, and supporting surface treatment processes.

Coolant delivery techniques:

CNC coolants present themselves in diverse forms, each tailored to specific machining requirements. These include air, mist, flood, high pressure, and minimum quantity lubricant (MQL). The choice of coolant delivery method hinges on factors such as the material being machined and the nature of the machining operation.

- Air: Primarily for cooling and chip removal, lacking lubrication properties.

- Mist: Low-pressure coolant suitable when chip removal and heat dissipation are secondary considerations.

- Flood: Offering lubrication and efficient chip removal, preventing re-cutting.
- High Pressure: Ideal for chip removal, particularly in deep cavity or drilling operations.
- MQL: Prioritizing environmental benefits by utilizing the minimum necessary coolant, minimizing costs and waste.

Types of coolants:

Coolants are classified into four main types, each formulated to address specific machining applications and materials.

- Soluble Oil: A prevalent water-soluble cutting fluid for general-purpose machining, forming emulsions with good heat transfer and lubricity.
- Synthetic Oil: The cleanest among cutting fluids, devoid of mineral oil or petroleum, boasting excellent cooling performance.
- Semi-synthetic Oil: A fusion of soluble oil and synthetic fluid, striking a balance between lubrication and reduced odor.
- Straight Oil: Immiscible with water, offering unparalleled lubrication while compromising somewhat on cooling.

Additionally, unconventional coolants such as carbon dioxide coolant and aerosol are gaining traction for their distinctive cooling approaches.

Effective Machine Coolant Systems and Management:

During machining, the coolant mixture inundates the work area, ensuring the removal of chips and particles. Efficient machine coolant systems, be they central or single-machine setups, demand vigilant monitoring, maintenance, and adjustments. Small systems, prevalent in some setups, necessitate meticulous management due to their susceptibility to contamination. Deviations from appropriate concentration levels can lead to corrosion, bacterial growth, and reduced tool life, emphasizing the significance of precise coolant management.

4 Hardware

4.1 PLC development environment

The development environment used in this project is the SIMATIC STEP 7 (Tia Portal), developed by Siemens. This environment allows the programmer to configure and program SIMATIC controllers, whether PLC- or PC based.
The following languages can be used to program controllers in this development environment:

- LD - Ladder Diagram
- FBL - Function block diagram
- SCL - Structured Control Language
- STL - Statement List
- SFC - Sequential Function Chart

4.2 Pumps

Pumps are mechanical devices which can move fluids from a certain position to another position, moving the fluids from a low-pressure area into and high-pressure area. Pump create hydraulic energy by converting the mechanical energy of the fluids.

Pumps can be categorized into two main groups:

- Dynamic
- Positive displacement

4.2.1 Dynamic pumps

Dynamic pumps function by transferring kinetic energy, the energy of motion, to the liquid by increasing the velocity of the flow. The flow of the fluid is diminished just before exiting the pump into the discharge pipe, thus converting the velocity increase into potential energy or pressure. This process involves three fundamental steps:

- Inflow of liquid into the pump
- Acceleration of liquid by the pump
- Deceleration or reduction of liquid speed, leading to increased pressure

The generated pressure facilitates the movement of the liquid through the system. In many dynamic pumps, centrifugal force plays a crucial role.
The following equation is derived from the Bernoulli's equation [3], and it describes that the output pressure is proportional to the square of the fluid velocity, meaning that small changes in fluid velocity can lead to large changes in pressure:

$$P = \frac{1}{2} p v^2 \tag{1}$$

Where

- P: Pressure generated
- p: Fluid density
- v: fluid velocity

The operation of dynamic pumps is governed by two major principles.

Axial pump

Axial pump are deployed for moving incompressible liquids at high pressures and to transport considerable flow rates at relatively short delivery heads. The axial pump achieves energy transfer solely through flow-related processes. The term "axial pump" is derived from the fact that the liquid is pumped parallel to the shaft of the pump, enabling the fluid to enter radially and be discharged axially.

Centrifugal pump

Centrifugal pump use rotating blades to impart energy from the motor to the fluid. In these types of pumps the fluid enters the pump from the reservoir through the impeller and exists at the top of the pump.
The impeller has three types:

- Open impeller
- Semi-open impeller
- Enclosed impeller

Through the rotation of the impeller centrifugal forces are generated in the fluid, at the inlet of the pump the pressure is decreased to lower levels than atmospheric pressure. This pressure difference between the outside pressure and the inlet pressure draws in the fluid from the reservoir.

4.2.2 Positive displacement pumps

Positive displacement pumps are specifically designed to only allow positive movement of the fluid, their internal structure stops the liquids from recirculating back into the inlet of the pump.
Positive displacement pumps work by drawing in the fluid by vacuum into a chamber or cavity, and once it is filled the cycle of pump causes the fluid present to increase in pressure. After the pressure increase the fluid is discharged via a discharge port and the cycle continuous.
Positive displacement pumps can further be divided into two main categories, rotary positive displacement pumps and reciprocating positive displacement pumps. The design of these differ in some parts but have the same basic three characteristics:

- Fixed amount of fluid transferred per cycle
- Constant pressure
- Fluid flow is proportional to speed

Rotary positive displacement pumps

Rotary positive displacement pumps employ the rotational motion of cogs or gears to transfer fluids, as opposed to the reciprocating back-and-forth motion used by reciprocating pumps. The rotating element provides a liquid seal with the pump casing and induces suction at the pump inlet.
Some of the designs belonging into this group are:

- Vane
- Internal and external gear
- Lobe
- Peristaltic
- Screw and progressing cavity

Reciprocating positive displacement pumps

A Reciprocating Positive Displacement pump operates through converting the rotary motion of the motor into a back-and-forth motion, also known as reciprocating motion. Some of the designs belonging into this group are:

- Piston
- Plunger
- Screw
- Progressing cavity

Advantages of positive displacement pumps

1. Accurate and predictable flow: The produced flow per cycle can reliably be calculated due to the fixed amount of fluid contained in the chamber.
2. Wide range of acceptable viscosity of the fluid: The performance of the pump is not affected by the viscosity of the fluid being pumped.
3. Consistent pressure: These types of pumps can produce high pressure of a wide range of duty points.

Disadvantages of positive displacement pumps

1. Restricted flow: Due to its design the flow rate of these types of pumps is inherently lower compared to other designs.
2. Difficult maintenance: Due to the intricate internal design the maintenance of these pumps are more labor intensive, service is more frequent.
3. Pulsating flow: The flow of liquids pumped by these kinds of pumps are pulsating, meaning pulse dampeners might be required based on the application.

4.2.3 Chosen pumps

For moving the emulsion from the barrel into the 'clean tank' a dynamic pump was chosen. This application requires no specialized pump, thus the cheapest option was chosen. For injecting the anti-foaming agent a positive displacement pump was chosen, these pumps can provide the necessary high pressure which is needed during the injection. The disadvantages of these kinds of pumps do not cause any problems in this type of application.

4.3 Concentration measurement

During design two options were considered for concentration measurement, one of which is a refractometer and the other is the combination of a mass flow meter and a volume flow meter.
Due to the high inaccuracy of the flow sensors together, it was decided that a refractometer would be used to achieve this measurement.

4.3.1 Coriolis flow meters

Coriolis flow meters directly measure the mass flow rate of fluids with the use of coriolis forces.

Coriolis force

Coriolis force (also called Coriolis effect), first described by Gustave-Gaspard Coriolis [5], is an inertial force. This effect describes an inertial force acting on a body in a rotating frame of reference, it acts to the right of the direction of body motion for counterclockwise rotation of the reference frame or to the left for clockwise rotation. This results in an apparent deflection of the path of an object that moves within a rotating system, the object does not actually does not actually deviates from its path, but appears to do so because the motion of the coordinate system.

Coriolis flow meter working principle

This measurement requires a tube on which a rotational oscillating force is acting. This rotational oscillating force is met by an equivalent Coriolis force produced by the fluid inside the tube, this causes the tube to deform, which is then measured and is proportional to the mass flow rate inside the tube.

Design of a coriolis flow meter

The most common design of the tube of coriolis flow meters is U-shaped, but it can be S-shaped or straight as well.
Inside the device, the flow tube is vibrated by a magnetic device, located at the bend of the tube, at its natural frequency.

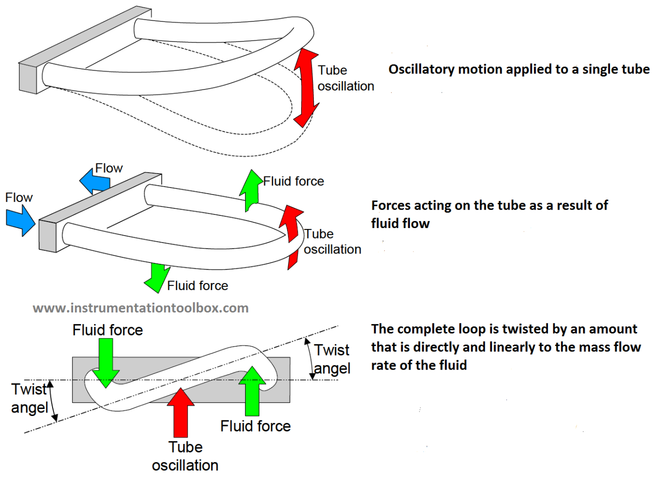


Figure 1: Operation of a coriolis flow meter

As seen on Figure 1. liquid which is flowing into the tube is forced to take up the momentum of the tube, the liquid resists this change by a exerting a downwards force on the tube. Exiting the tube, the liquid resist having its vertical moving decreased by the tube, and exerts an upwards force on the tube. These two phases cause the tube to twist, this twisting motion is directly proportional to the flow rate inside the tube.
Magnetic sensors located on the inlet and the outlet of the tube measure the tube velocities, which change with the tube twist. The electronics unit of the sensor is then fed these measurements, and converts them to a voltage which is proportional to the mass flow rate. In practice two identical tubes are used, oscillating in opposite directions. This setup allows for measurement which is more resilient for external vibrations and temperature changes. Unlike with a single tube, the sensors measure their relations to each other rather then to a fixed plane.

4.3.2 Orifice meter

Working principle of orifice meter

Orifice flow meters introduce a restriction to a pipe in form of a orifice plate. Due to this plate a differential pressure can be measured across the orifice plate. This differential pressure is linear and is directly proportional to the flow rate of the median inside the pipe.

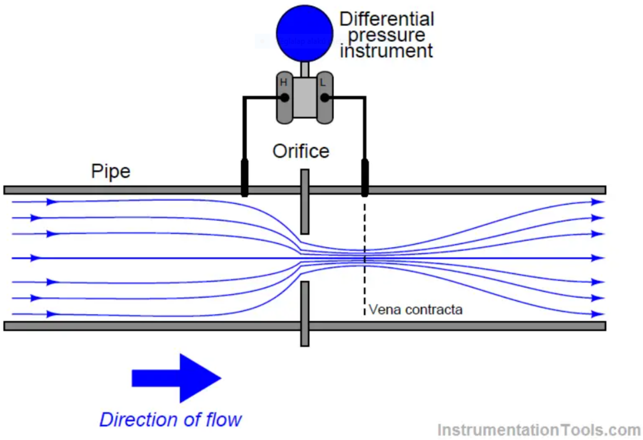


Figure 2: Operation of a orifice meter

Before the orifice plate the velocity of the median decreases and the pressure increases, after the orifice plate the velocity increases the the pressure drops. This pressure drop is is proportional to the flow rate inside of the tube. This change can be written down by the Bernoulli equation.

$$P_1 + \frac{1}{2} * pv_1^2 + pgh_1 = P_2 + \frac{1}{2} * pv_2^2 + pgh_2 \tag{2}$$

Bernoulli's principle

Bernoulli's principle [6] describes the horizontal flow of fluids in a pipe which changes diameters as it relates to pressure. Higher velocity fluids have lower pressure compared to lower velocity fluids.

4.4 Refractometers

Working principle of refractometers

Refractometers work on the principle that each material has its own refractive index. The refractive index is a constant, dimensionless number, which signifies the speed of light as it travels through a given median in relation to a reference medium (usually either vacuum or air). As the optical density of a medium decreases, the speed of light increases in the medium, causing the refractive index to decrease.
The refractive index of a medium also depends on the wavelenght of the light and the temperature of the medium.
The working principle of refractometers is based on the Snell's law, light travels slower in optically dense medians, and travels faster in optically less dense medians. With this change in speed also comes a change in direction, and at a certain angle of incidence, the light does not refract in the second medium at all, but reflect entirely. This angle at which this occurs is known as the critical angle and is measured by refractometers.

Snell's law

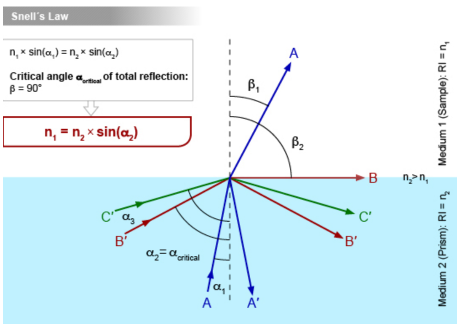


Figure 3: Incoming light rays are either totally reflected ($\alpha > \alpha$critical) or partly refracted and partly reflected ($\alpha < \alpha$critical), depending on their angle.

In Figure 3, beam A strikes interface medium 1 (with refractive index = n1) and medium 2 (with refractive index = n2, where $n2 > n1$) at the incident angle $\alpha 1$. This results in the partial reflection of both (beam A') and (beam A at angle $\beta 1$) at the boundary surface.
At a certain angle of incidence $\alpha 2$, one part of the light beam is reflected and another part is refracted exactly along the interface of the two media. This is known as total reflection and the angle is referred to as the critical angle of total reflection.
When the beam is incident at an angle greater then αcritical, the light beam will be entirely reflected (beam C').
Snell's law [7] can be applied to determine the RI of medium 1. The law states that the ratio of the RIs is equal to the inverse ratio of the sinus of angles $\alpha 1$ and $\beta 1$.

$$\frac{n_1}{n_2} = \frac{sin\alpha_1}{sin\beta_1} \tag{3}$$

When α 2 = α critical, the angle $\alpha 1 = \beta 1 = 90°$. Substituting these values into Snell's law gives

$$n_1 = n_2 * sin\alpha_{critical} \tag{4}$$

Measuring the RI of medium 2 and the critical angle of total reflection αcritical can therefore yield the RI of medium 2.

Schematic setup of refractometers

A refractometer's main part is a light source, which is filtered to a single wavelength (usually 589nm). This filtered light is then directed toward the interface between the prism and the sample by a converging lens. This creates a range of incidence angles, where angels which are smaller than the critical angle experience full reflection. This phenomenon can accurately be measured by a Charge-coupled Device (CCD) sensor, which can determine the exact angle αcritical at which light begins to be totally reflected by measuring the intensity of the reflected light. Based on the measured angle, the refractive index of the material can be calculated. The angle depends on the ratio of the reflective index of the prism (which is known) and the refractive index of the sample.

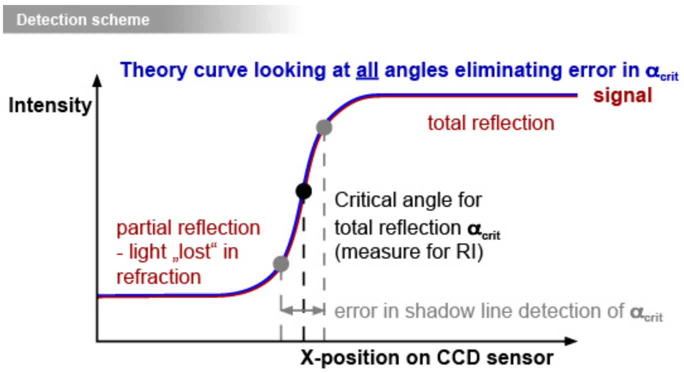


Figure 4: Diagram of CCD sensor critical angle detection. A theoretical curve is fitted to all collected data points and from this the critical angle αcritical can be determined precisely.

On Figure 4. the resultant step in light intensity can be seen. The determination of the critical angle is achieved by applying a theoretical "Fresner" curve to the video signal of the CCD sensor. Compared to shadow line detection this method guarantees a more accurate measurement of the refraction index.

As seen on Figure 5., the measured sample is in contact with the prism. Incoming light of

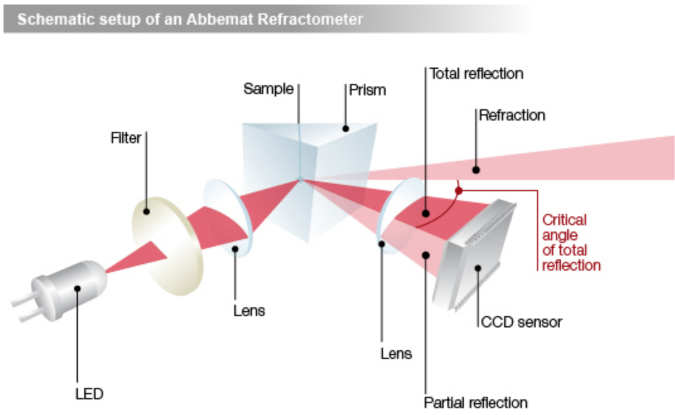


Figure 5: Schematic setup of a refractometer

greater angles than the critical angle are fully reflected, light of lesser angles are partially refracted through the sample. The reflected light is then measured by a high-resolution sensor array.

Refractive index's dependence on wavelength

Dispersion relation describes the fact that most materials refractive index varies with

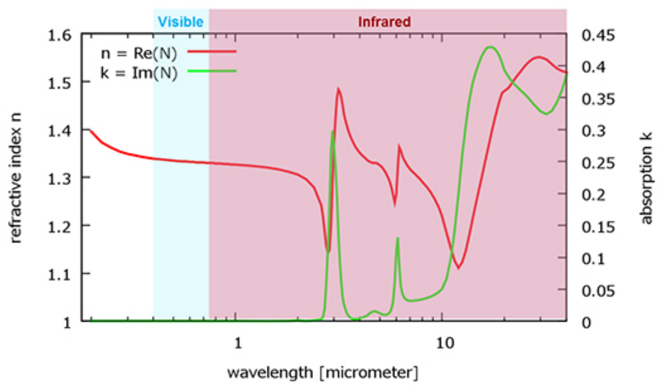


Figure 6: Dispersion curve of water

different wavelengths. Every material has its own so called dispersion pattern, which describes how the refractive index changes with the wavelength.
On Figure 6., the dispersion curve of water can be seen, the absorption is indicated with a blue curve and the dispersion with red.
The precision of the wavelength is guaranteed by an interference filter, this ensures the

accurate determination of the refractive index of the sample. While most refractometric measurements are done at 589 (or 589.3) nm, the wavelength of the sodium D-line, some applications require other wavelengths.

Refractive index's dependence on temperature

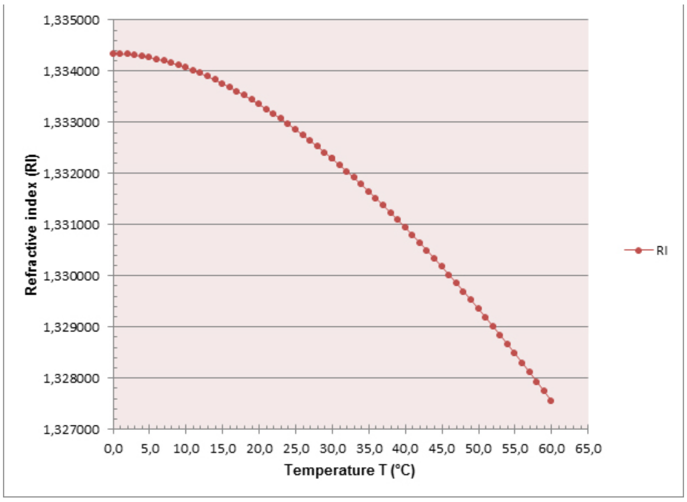


Figure 7: Refractive index (λ = 589.3nm) of water at temperature T relative to vacuum, calculated according to Tilton and Taylor (1938)

The refractive index of a material is also influenced by temperature, so it is important to account for it during the whole measurement. Older instruments got around this problem by applying water baths, newer instruments often employ Peltier modules to regulate the temperature during the measurement, the prism and the sample is kept at a constant temperature and is monitored by high-precision temperature sensors.

Chosen sensor

The chosen sensor for this project is the iPS CL in-line Process Sensor for Cooling Lubricant, produced by Schmitdh Haensch.

SPECIFICATIONS	IN-LINE PROCESS SENSOR - COOLING LUBRICANTS
Measuring scales	Cooling lubricant Scale %
Measuring range	0 - 25 Brix
Resolution	0.1 Brix
Accuracy	± 0.3 Brix at 5°- 45° Celsius
Temperature Accuracy	+5 °C
Temperature Resolution	± 0,1°
Process temperature	+5° C to + 35°C
Ambient temperature	+10° C to + 40°C
Max pressure	6 bar 10 bar < 12h
Power supply	24 < 75mA (20V - 28V)
Light source	589 nm LED
Analog data outpt	4–20 mA - active output 300Ω, 2mA output if outside measuring ranges or error condition
Process condition	optional: VariVent-Inline (Tuchenhagen) or APV-Inline (APV)
Other options	Cleaning units (please contact SCHMIDT + HAENSCH for more detail)
Dimensions	165 mm x 45 mm (length x diameter)
Weight	500 g

Figure 8: Datasheet of refractometer

This sensor is purpose built for the measurement of cooling lubricant concentrations.

4.5 pH meter

For the measurement of organic matter build-up a pH meter was decided on. The organic matter changes the pH level of the emulsion, thus allowing us to detect the presence of it. pH meters measure Hydrogen ion concentration to determine the acidity and alkalinity of a solution.

Working principle of pH meters

pH Meter Principle: Two electrodes are immersed in a solution, one is a glass electrode and the other one is a reference electrode. An electrochemical reaction occurs between the glass electrode and the hydrogen ions in the solution, resulting in a small potential which is proportional to the hydrogen ion concentration in the solution. This potential is then measured against the reference potential which the reference electrode provides. The difference between these two potentials is called the pH unit.

Key Components or parts of pH instrument

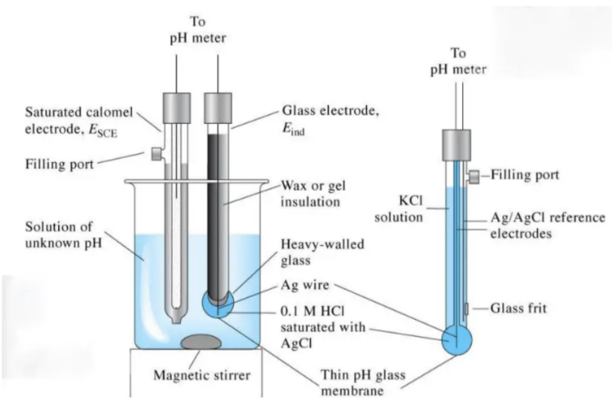


Figure 9: Parts of a pH meter

pH Sensor: A combination electrode consisting of a reference electrode and a glass electrode. It measures the voltage difference between the electrodes which is directly to the pH level of the solution.

Temperature probe: A temperature probe is used to measure the temperature of the solution during measurement. Allows the measurement device to make corrections accounting for the changes in temperature.

pH Meter: It is a device which displays the pH level of a solution, contains the pH probes and a voltmeter.

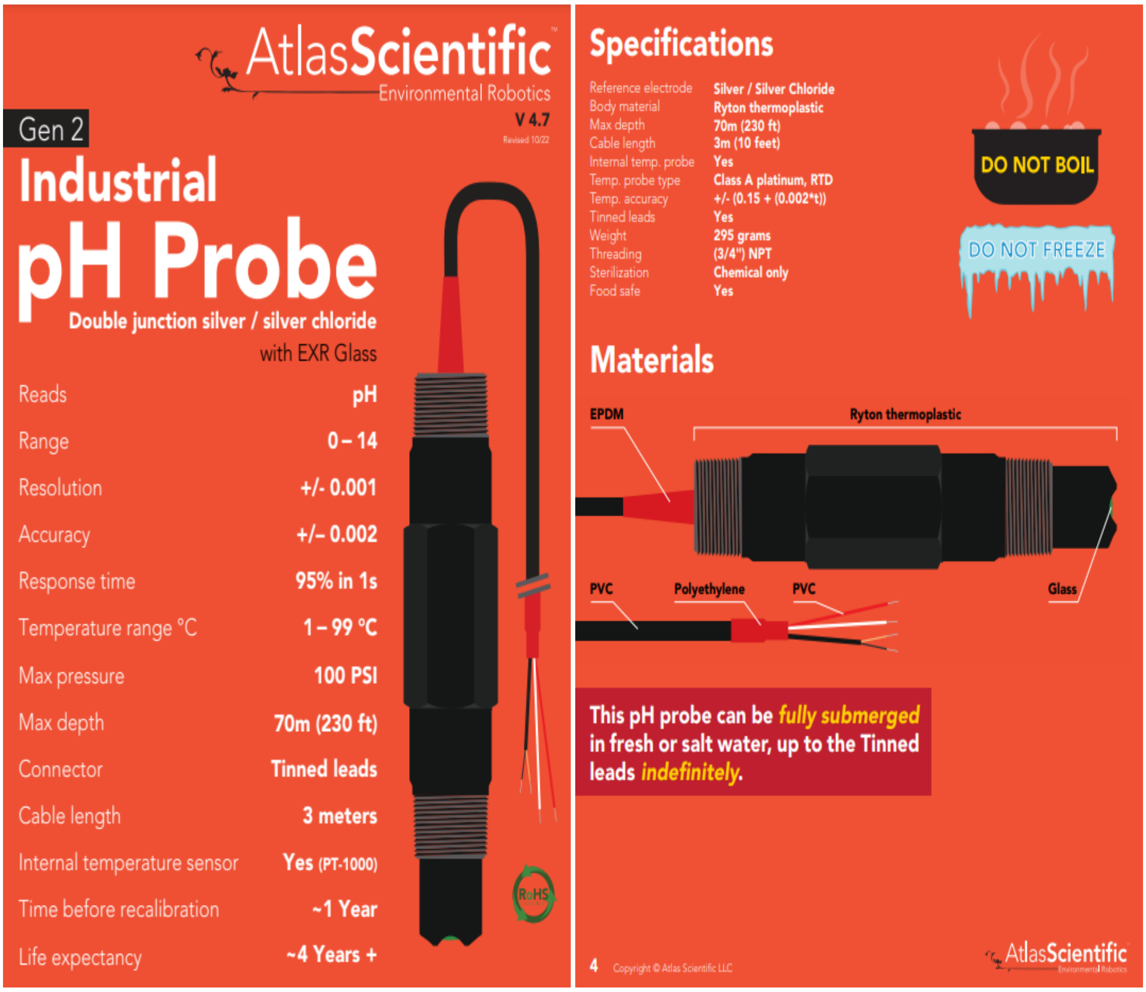
Electrodes: The glass electrode is made up of a thin glass tube and a glass bulb at the end of the glass tube. The glass bulb contains potassium chloride with a pH of 7 and silver chloride attached to a silver element. The silver chloride and the silver element are responsible for generating the voltage which is then measured.

The reference electrode is a glass tube containing potassium chloride solution and a mercury chloride block. This electrode is responsible for providing stable zero-voltage.

Junction: It is the point at which the two electrodes meet. It is usually made out of either ceramic or a porous material.

Chosen pH meter

The chosen pH meter for this project is the Industrial pH Kit produced by Atlas Scientific, this bundle contains a pH probe and an industrial pH transmitter. The ph transmitter allows for easy connection to a PLC.



4.6 Level sensor

For the level measurement in the clear tank an ultrasonic level transmitter was chosen, since we need constant contactless measurement of the level of emulsion in the tank. For the level measurement in the barrel containing the emulsion we are using a magnetostrictive level transmitter, since it provides us with a portable solution.

4.6.1 Ultrasonic level transmitter

An ultrasonic level transmitter works by emitting a high-frequency pulse, usually between 20kHz to 200kHz, and then measuring the time it takes for the signal to reach and then bounce back form the level surface. The distance of the surface from the sensor is determined by dividing the time between the pulse and its echo by two.

Working of a ultrasonic level transmitter
Ultrasonic level transmitters are usually mounted on the top of the tank, on a flange.

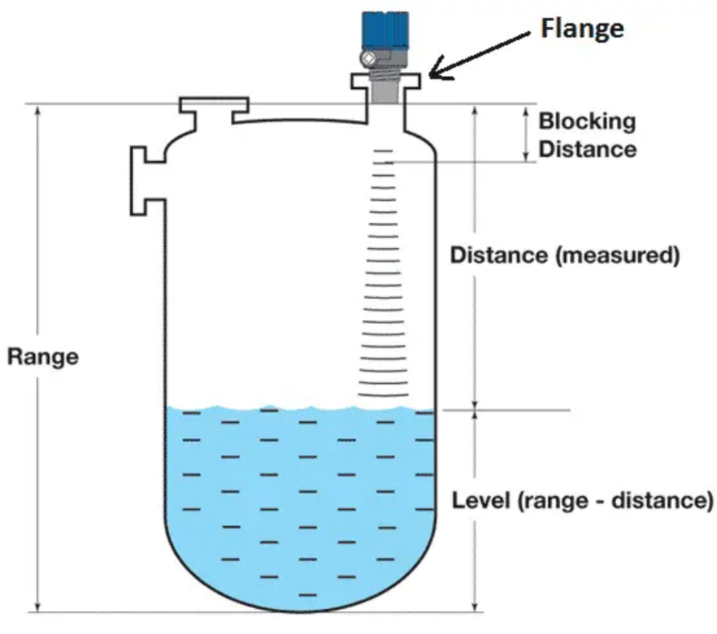


Figure 11: Working of a ultrasonic level transmitter

The transmitter produces and measures the high-frequency pulses by a piezoelectric transducer. During measurement the sensor physically vibrates due to the high amplitude of the returning pulse. To combat the effects of this phenomenon a so called ”blocking distance” is introduced below the sensor, which is usually between 300mm to 450mm, this distance is ignored by the sensor to prevent inaccurate measurement by the sensor.

Using the formula: measured distance $= \frac{speed*time}{2}$ the distance is calculated by the ultrasonic level transmitter.

4.6.2 Magnetostrictive level transmitter

Magnetosriction is a unique property of ferromagnetic materials, which are attracted to and are capable of forming permanent magnets. Ferromagnetic elements in these materials contract or expand when magnetic fields are introduced, converting electromagnetic energy into vibrations or mechanical energy.

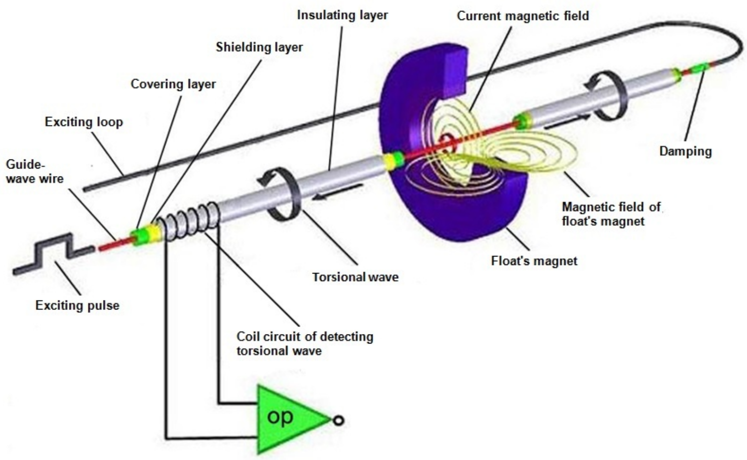


Figure 12: Magnetostrictive level transmitter

Magnetostrictive float level measurement sensors consist of three primary components.
Firstly, there is a hollow stem that houses a waveguide made from ferromagnetic material, which is suspended within the liquid being measured.
Secondly, a hollow float moves along the stem's surface, corresponding to the liquid's level. Enclosed within the float is a permanent magnet. As the float moves, the magnetic field of the magnet alters the alignment of the waveguide's magnetic molecules within the stem.
The third component comprises the device electronics. These electronics generate periodic electromagnetic pulses. These pulses travel through the waveguide, generating their own magnetic field. When the pulses reach the float, the conflicting magnetic fields induce vibrations in the waveguide, resulting in a torsional stress wave or strain pulse propagating back up the waveguide at a known speed. A component of the electronics detects the strain pulse, converting the mechanical energy into an electronic signal. Finally, an electronic chip measures the time interval between the initial pulse and the returning strain pulse, allowing for precise determination of the distance between the device electronics and the float.

Chosen magnetostrictive level transmitter

The chosen sensor the Magnetostriktív helyzetmérő rendszerek mobil hidraulikához by Balluff. This level transducer allow for the precise measurement of emulsion level for up to 2 meters, the measurement height can be customized. The height of the usual steel made barrel is 820cm so it is within the range which we can measure.

Magnetostrictive Sensors

BTL6 -E- Series - Analog current

BALLUFF

Basic features

Approval/Conformity	l = KA: CE + UKCA + cULus + WEEE l = LA: CE + UKCA + WEEE
Magnets, number (factory setting)	1
Magnets, number max.	1

Electrical connection

Polarity reversal protected	Ub up to 40 V
Short-circuit protection	to GND and to 36 V DC

Electrical data

Current consumption max. at 24 V DC	60 mA
Inrush current	≤ 2.5 A/2 ms
Load resistance RL max.	500 Ohm
Operating voltage Ub	10...30 VDC
Output signal adjustable	no
Overvoltage protection	Ub up to 36 V
Switch-on delay max.	600 ms
Voltage-proof up to (GND to housing)	500 V DC

Environmental conditions

Ambient temperature	-40...85 °C
Cable temperature, fixed routing	l = KA: -40 °C ... 80 °C l = LA: -40 °C ... 135 °C
EN 55016-2-3, Radiation	For industrial and residential use
EN 60068-2-27, Continuous shock	50 g, 2 ms
EN 60068-2-27, Shock	100 g, 6 ms
EN 60068-2-6, Vibration	12 g, 10…2000 Hz
EN 61000-4-2, ESD	Severity Level 3
EN 61000-4-3, RFI	Severity Level 3
EN 61000-4-4, Burst	Severity Level 3
EN 61000-4-5, Surge	Severity Level 2
EN 61000-4-6, High-frequency fields	Severity Level 3
EN 61000-4-8 Magnetic fields	Severity Level 4
IP rating	IP67
Relative humidity	≤ 90 %, non-condensing
Storage temperature	-40...100 °C
Temperature coefficient typ.	25.0 µm/K at 50% of nominal stroke 500mm

Functional safety

MTTF (40 °C)	101 a

Interface

Interface	Analog, current

Material

Cable flame-resistant	l = KA: IEC 60332-1
Cable jacket, material	l = KA: PUR l = LA: ETFE
Cover material	1.4305 stainless steel
Housing material	1.4404 stainless steel
Material flange	1.4404 stainless steel
Protection tube material	1.4571 stainless steel

Mechanical data

Installation length from contact surface	nnnn + 94 mm
Pressure rating max.	g ≠ 8: 350 bar g = 8: 250 bar
Pressure rating, note	when installed in hydraulic cylinder
Speed detectable max.	10 m/s

Range/Distance

Linearity deviation	nnnn = 0050…0500: ± 200 µm nnnn > 0500: ± 0.04% FS (typ.± 0.02% FS)
Measuring length	50...2000 mm
Repeat accuracy	± 5 µm
Resolution, position	depending on controller (only limited by repeat accuracy)
Sampling frequency max.	nnnn = 50…1300: 1000 Hz nnnn = 1301…2000: 500 Hz

Figure 13: Datasheet

5 Software

5.1 PLC program

The PLC program of this project contains 4 main parts, the first of which is a block called Scaling. This program block is responsible for taking the analog inputs (4-20mA) and converting them into physical values.

The second main part of the program is the so-called Daily pumping. This part of the code is responsible for the filling process of the emulsion tank and achievement of the desired solution of the emulsion.

The third large part of the program is responsible for providing feedback on the current and the historical state of the filling process.

The last larger part of the program is the anti foaming. This block is responsible for the injection of anti foaming agent into the ’dirty tank’.

Accompanying these blocks are smaller program blocks which activate and manipulate the state of the time of day interrupt.

5.1.1 Scaling

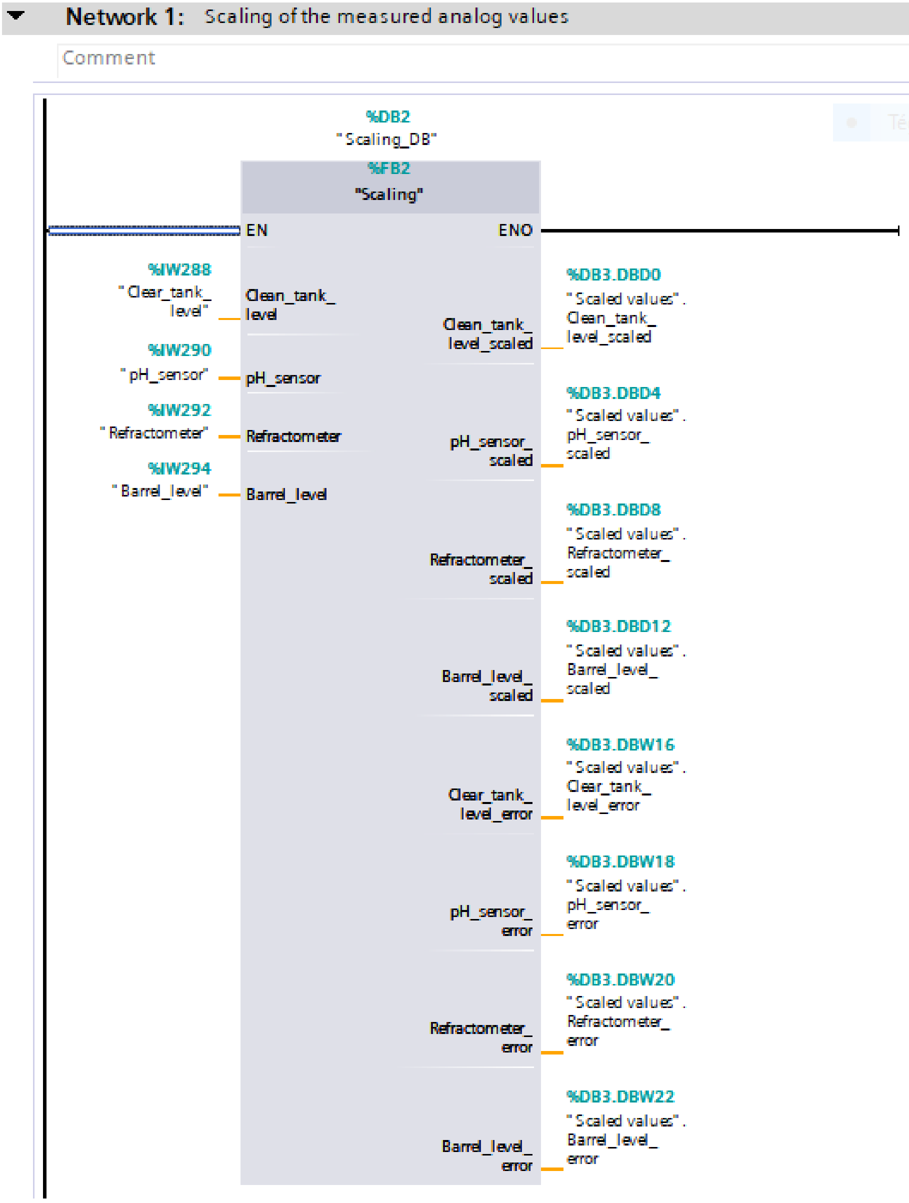


Figure 14: Scaling function block

This function block recieves the input values from the sensors and then turns them into physical values. This conversion is achieved with scale instructions, it converts the integer at the IN parameter into a floating-point number, which can be scaled in physical units between a low limit and a high limit.

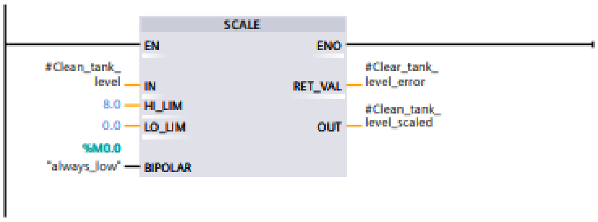


Figure 15: Example of a Scale function block

These instructions have 6 parameters, an input values (int) which is to be converted. Two input parameters are responsible for specifying the low limit and high limit of the value range to which the input value is scaled. Another parameter indicates if the value at the IN parameter is to be interpreted as bipolar or unipolar. These two states are:
0 : Unipolar, K1 constant has value 0.0 and K2 constant has value +27648
1 : Bipolar, K1 constant has value -27648 and K2 constant has value +27648
The instruction has 2 output parameters one of which is an error value and the other is the output value in Real. The output value is calculated based on the following equation:

$$OUT = [((FLOAT(IN)–K1)/(K2–K1)) * (HI_{LIM}–LO_{LIM})] + LO_{LIM} \tag{5}$$

Four sensor inputs are scaled in this block:
The level inside of the ’clean tank’, this value is scaled between 0 and 8 meters.
The level inside of the barrel, this value is scaled between 0 and 840mm.
The pH of the emulsion which is scaled between 0 and 14.
The input of the refractometer which measures the concentration of the emulsion, and is scaled between 0 and 25 Brix.

Name	Data type	Offset	Start value	Retain	Accessible from HMI/OPC UA	Writable from HMI/OPC UA	Visible in HMI engineering	Setpoint	Supervision	Comment
▼ Input										
Clean_tank_level	Int	0.0	0	True	True	True	True	False		Level inside the tank, unscaled
pH_sensor	Int	2.0	0	True	True	True	True	False		pH of the emulsion, unscaled
Refractometer	Int	4.0	0	True	True	True	True	False		Concentration of the emulsion, unscaled
Barrel_level	Int	6.0	0	True	True	True	True	False		Level inside the barrel, unscaled
▼ Output										
Clean_tank_level_scaled	Real	8.0	0.0	True	True	True	True	False		Level inside the tank, scaled
pH_sensor_scaled	Real	12.0	0.0	True	True	True	True	False		pH of the emulsion, scaled
Refractometer_scaled	Real	16.0	0.0	True	True	True	True	False		Concentration of the emulsion, in brix
Barrel_level_scaled	Real	20.0	0.0	True	True	True	True	False		Level inside the barrel, scaled
Clear_tank_level_error	Word	24.0	16#0	True	True	True	True	False		
pH_sensor_error	Word	26.0	16#0	True	True	True	True	False		
Refractometer_error	Word	28.0	16#0	True	True	True	True	False		
Barrel_level_error	Word	30.0	16#0	True	True	True	True	False		
InOut										
Static										

Figure 16: Inputs and outputs of the scaling function block

These output values are then stored in a data block named 'Scaled values'. These values are used later on to control the concentration of the emulsion and to activate alarms.

5.1.2 Daily pumping

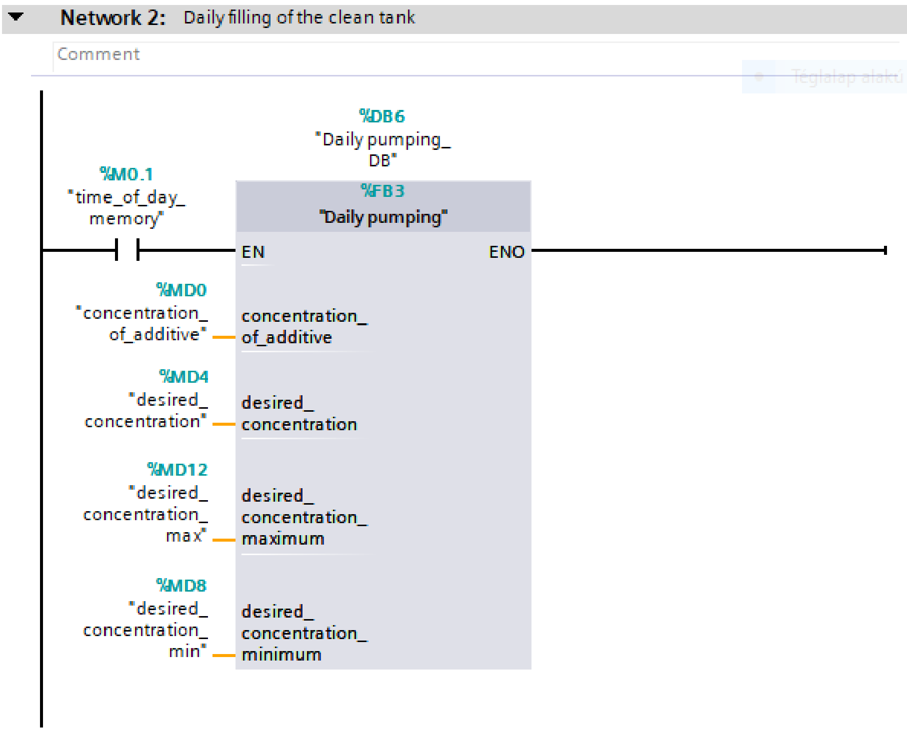


Figure 17: Daily pumping function block

This program block is activated by the time of day interrupt and is responsible for activating the pump which syphons additional emulsion into the 'clean tank' if needed.

Name	Data type	Offset	Default value	Accessible from HMI/OPC UA	Writable from HMI/OPC UA	Visible in HMI engineering	Setpoint	Supervision	Comment
▼ Input									
concentration_of_additive	Real	0.0	0.0	True	True	True	False		The additive emulsion's concentration in %
desired_concentration	Real	4.0	0.0	True	True	True	False		The desired concentration of emulsion inside the clean tank.
desired_concentration_maximum	Real	8.0	0.0	True	True	True	False		The desired maximum concentration of emulsion inside the clean tank.
desired_concentration_minimum	Real	12.0	0.0	True	True	True	False		The desired minimum concentration of emulsion inside the clean tank.
Output									
InOut									
Static									
▼ Temp									
clean_base	Real	0.0							Base of tank in m^2
clean_1000L	Real	4.0							Content of tank in m^3
clean_L	Real	8.0							Content of tank in liters
additive_needed	Real	12.0							Additive needed in liters
tank_level_needed	Real	16.0							Tank level needed to achieve the desired concentration
div_top	Real	20.0							Top part of the end division
div_bottom	Real	24.0							Bottom part of the end division
tank_level_mem_bit	Real	28.0							Memory bit used to store the value of the tank level at the start of the measurement
Refractometer_mem_bit	Real	32.0							Memory bit used to store the value of the concentration inside the tank
▼ Constant									
clean_width	Real		8.0						Width of the tank
clean_lenght	Real		10.0						Leght of the tank
maximum_water_level	Real		7.0						Maximum allowed tank level

Figure 18: Variable table of the daily pumping function block

It has four input values which are:

- Concentration of the additive
- Desired concentration
- Desired concentration maximum
- Desired concentration minimum

With these variables the desired and the additive concentrations can be customized to fit the specifications of individual machines.
Additionally the program block also uses the scaled values of the sensors which are stored in a seperate data block.

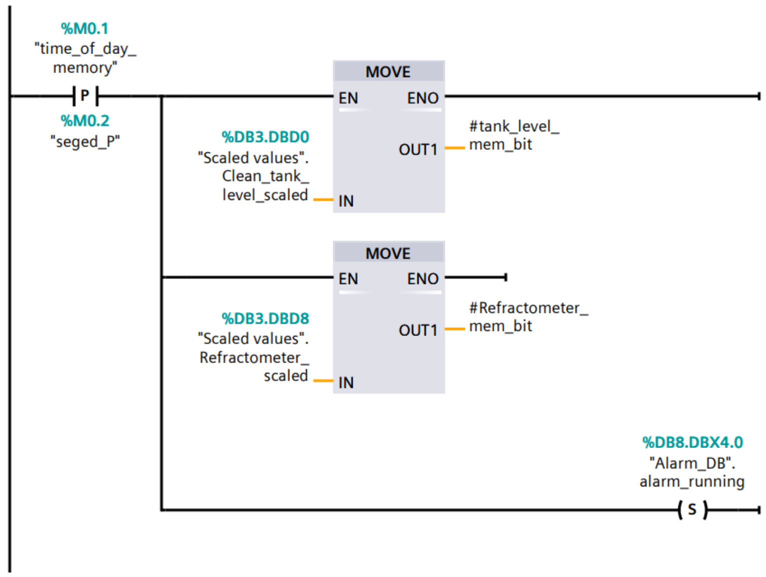


Figure 19: First network inside the daily pumping function block

Before calculation the program block moves the current tank level and the concentration into memory bits to be later used in the calculation. Additionally to this an alarm bit which indicated that the filling process is running is set.

The program block calculates the amount of additional emulsion needed to achieve the desired concentration based on the current level and concentration inside of the tank. After this the block calculates the additional emulsion necessary to achieve the desired concentration.
The calculation runs according to the following formula:

$$\frac{CurrentConcentration - DesiredConcentration}{DesiredConcentration - Concentrationof Additive} = AdditionalAdditiveNeeded \tag{6}$$

After this the additional additive needed is added to the clean tank level memory bit to calculate the 'clean tank' level needed to achieve the desired concentration.

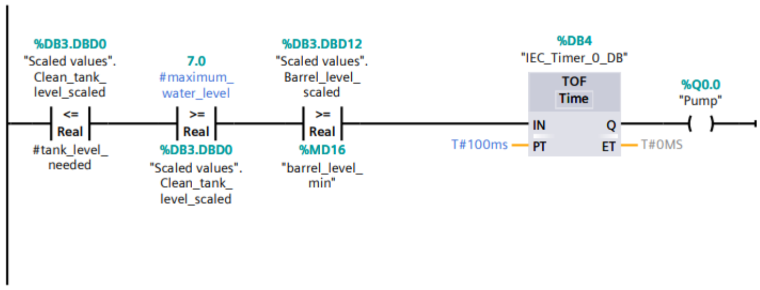


Figure 20: Filling the the tank

Then the filling is started, the program monitors the current level inside of the barrel and the ’clean tank’, if the barrel level would fall bellow the minimum allowed level or the ’clean tank’ level would exceed the maximum allowed level the filling process stops, else the pump is ran until the calculated ’clean tank’ level is reached.

To a falling edge trigger of the pump the current level and concentration inside the clean

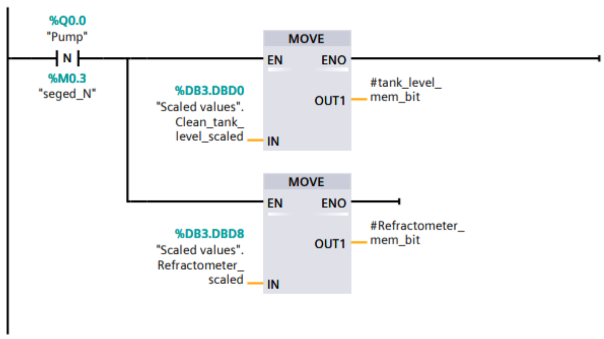


Figure 21: Moving the current values after the filling process into the memory bits

tank are moved into a memory bit once again.

After the initial calculation and filling cycle the process is repeated until the concentration is within an acceptable range after a small delay to reduce the likelyhood of errors due to the waves generated in the emulsion while filling.

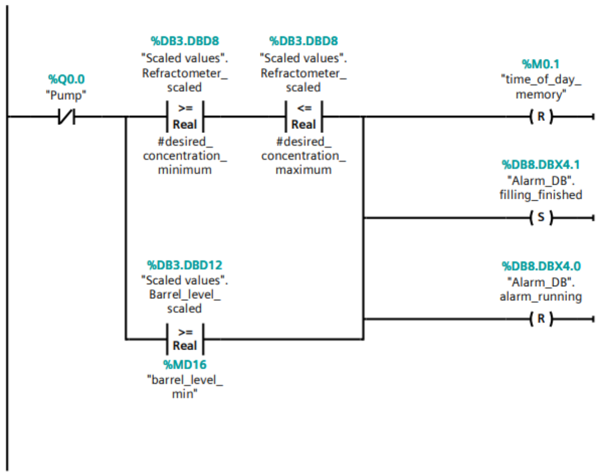


Figure 22: Setting and resetting the necessary variables

The last part of the block checks whether the filling process was successful and resets the alarm bit which indicated that the filling process is running and the time of day interrupt. Additionally is sets a alarm bit which shows that the filling process has successfully concluded.
The process runs according to the following flow chart:

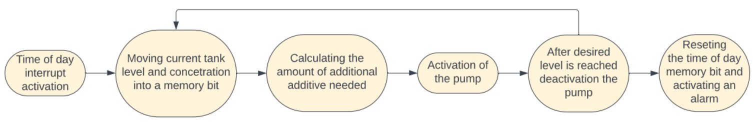


Figure 23: Flow chart of the daily pumping

5.1.3 Alarms

Figure 24: Alarm function block

This program block is responsible for monitoring the current state of the program and generating alarm when necessary.

▼ Input									
Clean_tank_level_scaled	Real	0.0	0.0	True	True	True	False		Level inside the clean tank
Barrel_level_scaled	Real	4.0	0.0	True	True	True	False		Level inside the barrel
Refractometer_scaled	Real	8.0	0.0	True	True	True	False		Concentration measured by the refractometer in brix
Pump	Bool	12.0	false	True	True	True	False		Pump running
desired_concentration	Real	14.0	0.0	True	True	True	False		The desired concentration of emulsion inside the clean tank.
desired_concentration_min	Real	18.0	0.0	True	True	True	False		The desired minimum concentration of emulsion inside the clean tank.
desired_concentration_max	Real	22.0	0.0	True	True	True	False		The desired maximum concentration of emulsion inside the clean tank.
maximum_clean_level	Real	26.0	0.0	True	True	True	False		Maximum allowed level in clean tank
pH_sensor_scaled	Real	30.0	0.0	True	True	True	False		pH of the emulsion, scaled
pH_max	Real	34.0	0.0	True	True	True	False		Maximum acceptable pH inside the tank
pH_min	Real	38.0	0.0	True	True	True	False		Minimum acceptable pH inside the tank
Foaming	Bool	42.0	false	True	True	True	False		Indicates when the anti foaming pump is on
Output									
▼ InOut									
▼ alarm_array_bool	Array[0..15] of Bool	44.0		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[0]	Bool	0.0		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[1]	Bool	0.1		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[2]	Bool	0.2		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[3]	Bool	0.3		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[4]	Bool	0.4		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[5]	Bool	0.5		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[6]	Bool	0.6		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[7]	Bool	0.7		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[8]	Bool	1.0		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[9]	Bool	1.1		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[10]	Bool	1.2		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[11]	Bool	1.3		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[12]	Bool	1.4		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[13]	Bool	1.5		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[14]	Bool	1.6		False	False	False	False		Boolean array used for storing the alarms
alarm_array_bool[15]	Bool	1.7		False	False	False	False		Boolean array used for storing the alarms
alarm_running	Bool	50.0	false	True	True	True	False		Indicates that the filling process is running
alarm_word	Word	52.0	16#0	True	True	True	False		Word used for storing the alarms, later used for the HMI
filling_finished	Bool	54.0	false	True	True	True	False		Indicates that the filling process has ended

Figure 25: Inputs and outputs of the alarm function block

The block produces ten alarm total which are stored in a bolean array and are later displayed on the HMI:

- Checking for higher than desired maximum concentration of the emulsion.
- Checking for lower than desired minimum concentration of the emulsion.
- Checking for foaming inside the ’dirty tank’
- Checking for barrel level below 25%
- Checking for barrel level below 10%

- Checking for barrel level below 5%
- Could not achieve desired concentration, ’clean tank’ is too full
- Could not achieve desired concentration, barrel level too low
- pH is outside of acceptable range
- Filling finished successfully

5.1.4 Anti foaming

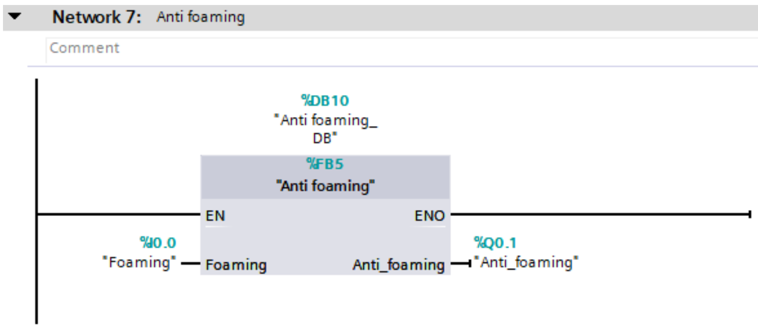


Figure 26: Anti foaming function block

This program block is responsible for monitoring the foam buildup inside the ’dirty tank’. When foaming is detected by the sensor after a small delay a pump is turned on to siphon anti foaming agent onto foam to eliminate the phenomenon.

5.1.5 Additional program blocks

These additional block are responsible for controlling the time of day interrupt used in daily pumping.
These block include:

- Set time of day
- Set time of day interrupt
- Activate time of day interrupt

Set time of day

This instruction has one input and one output, the input is the date and time which is to be set and the put is the status of the instruction.

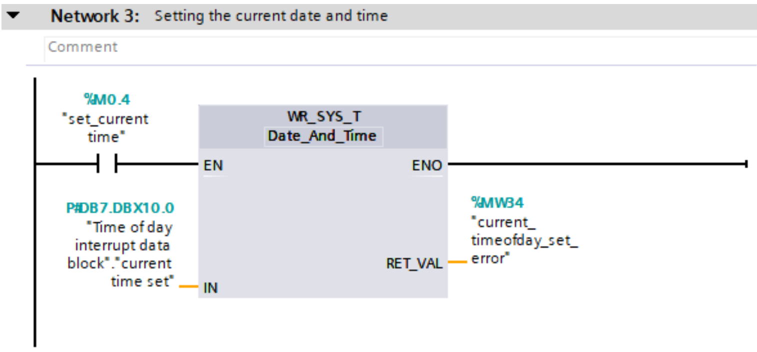


Figure 27: Setting current time of day

This instruction is used for setting the current date and time for the PLC, the input value is received through the HMI.

Set time of day interrupt

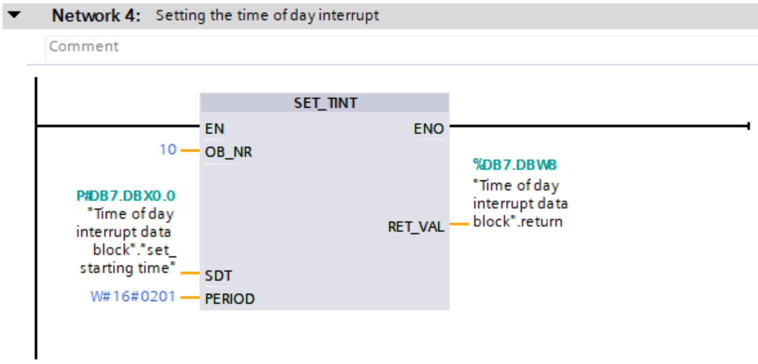


Figure 28: Setting time of day interrupt

This instruction sets the starting date and time and the period of the time of day interrupt. It has three input values and one return value:

- OB-NR: Number of the OB started at the time SDT + multiple of PERIOD (OB 10 to OB 17).
- SDT: Starting date and time
- Period: specifies the period of the time of day interrupt (once, once every minute, once every hour...)

Activate time of day interrupt

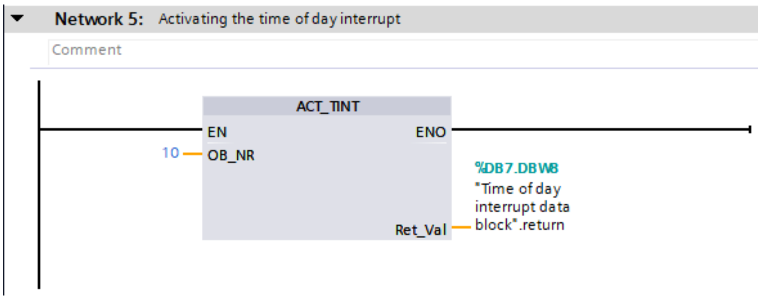


Figure 29: Activating time of day interrupt

This instruction activates the time of day interrupt, without this instruction the time of day interrupt is never called.

5.2 HMI

The Human-Machine Interface's (HMI) main purpose in our case is to provide useful information for any personnel monitoring the filling process. Additionally to monitoring the HMI also allows for certain variables of the program to be changed.

5.2.1 Start screen

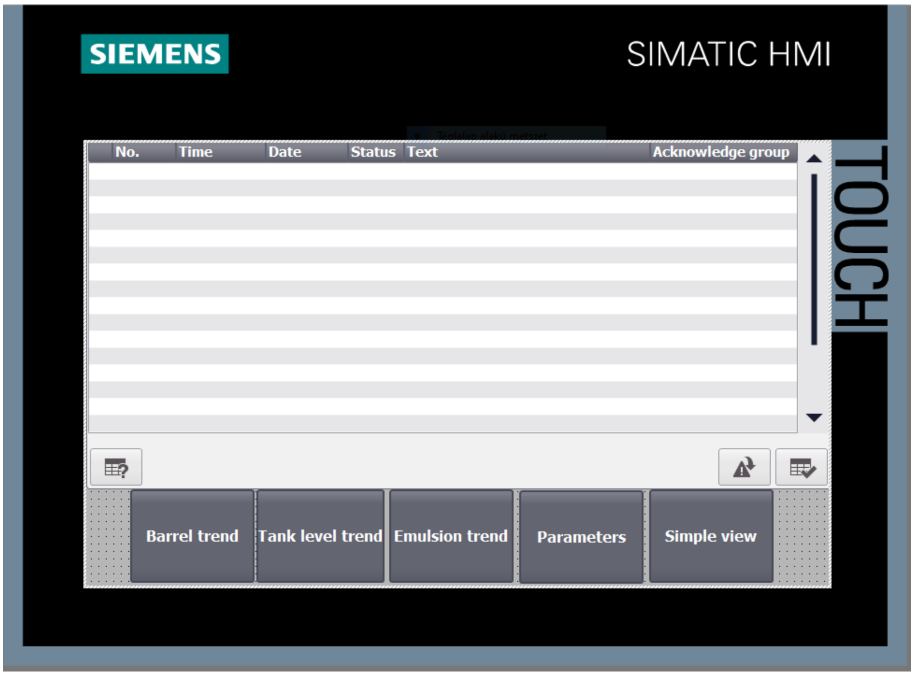


Figure 30: Start screen

The initial display, the start screen, is comprised of two primary components: an alarm view and a set of five distinct buttons. The alarm view allows users to easily control and change alarm settings right from the alarm view.
These buttons serve as navigational tools, enabling users to transition between different screens or sections of the application.

5.2.2 Simple view screen

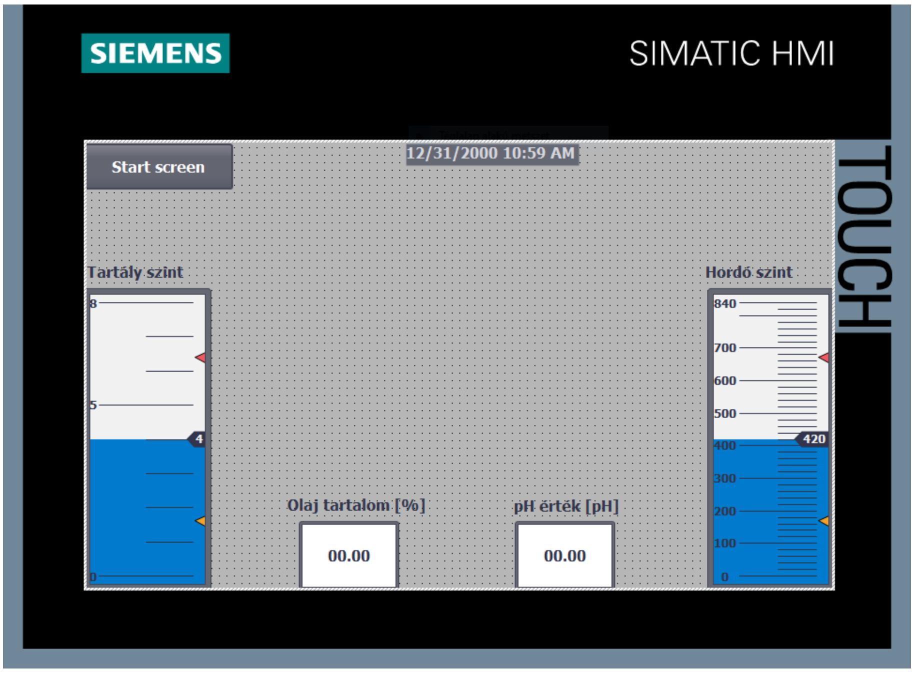


Figure 31: Simple view screen

The simple view screen serves the purpose of offering a snapshot of the present condition of the cooling lubricant system. Within this interface, users can access vital information such as the current time, the level of lubricant in the barrel, the overall tank level, as well as details regarding pH levels and emulsion concentration. This display enables effective monitoring and management of the cooling lubricant system.

5.2.3 Change parameters screen

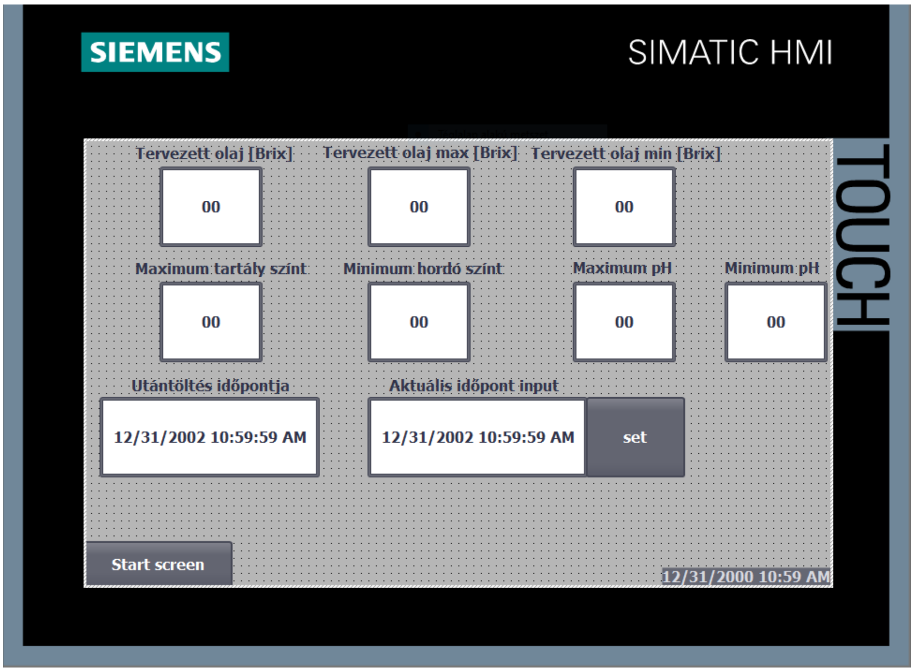


Figure 32: Change parameters screen

The Change Parameters screen enables users to modify specific parameters related to the cooling control process. Users can adjust the target concentration, as well as the minimum and maximum concentrations, dynamically in response to changes in emulsion standards. Additionally, when using a different barrel, the permissible minimum and maximum barrel levels can be easily adjusted. This screen also allows users to specify the current time and filling time if necessary, and to set both maximum and minimum pH values.

5.2.4 Trend view screens

In addition to the other screens, there are dedicated screens for viewing trends in barrel level, emulsion concentration, and tank level. These trend views serve the dual purpose of monitoring the filling process and identifying any discrepancies or malfunctions.

6 Summary

This paper explores the implementation of an automated quality control system for monitoring the cooling lubricant of a CNC machine. The automation is accomplished through the integration of a PLC and an array of sensors, providing essential data for effective quality control of the cooling lubricant.
The initial section of the paper presents a comprehensive overview of CNC machines, their cooling systems, and emphasizes the significance of maintaining the proper emulsion composition.
The hardware section delves into the operational principles of the components used in the project, along with the rationale behind the selection of these components.
The software part of the paper provides a detailed description of the PLC program specifically designed for this project. This program facilitates the automation of quality control for the emulsion composition. Additionally, it features a Human-Machine Interface (HMI) for user-friendly monitoring and adjustment of specific parameters within the automated system.

7 Further development

This project can be further developed by scaling the process control to include the whole production hall. A centralized cooling lubricant distribution system could be developed. This development would decrease the budget spent on expensive sensors, but would lead to other complications. These complications include routine maintenance, space restraints and more points of failure. Scaling to centralized cooling lubricant distribution system would cause routine maintenance to lead to a plant-wide shutdown costing considerable lost production capability for the company. Furthermore a centralized cooling lubricant distribution system would take considerable amount of precious space on the floors.
Another possible upgrade for this system is centralized data logging, a central data base could be developed to keep track of historical data of cooling lubricant usage and would allow for centralized monitoring of the current state of the composition of the emulsion.

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