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Industrial Electrical Engineering and Automation

Motion Controlled Cleaning of Large Tanks

Mattis Wahlby

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

Master Thesis

Motion controlled cleaning of large tanks

Division of Industrial Electrical Engineering and Automation, LTH, Lund University, SE-221 00 Lund, Sweden

Examiner:
Ulf Jeppsson
Supervisors:
Gunnar Lindstedt
Jonas Pettersson
Opponent:
Mikael Henriksson

Author:
Mattis Wahlby

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Abstract

Reduction of the cleaning time is an important issue for companies using large tanks. A common solution is a stationary pipe going into the tank with a cleaning nozzle mounted on the end. Today the spray pattern of most cleaning systems is fixed. It would be beneficial to adjust the cleaning cycles so that the most soiled places of the tank get extra attention without increasing the total cleaning time of the tank.

This thesis develops and implements an algorithm for an arbitrary cleaning pattern for a tank with the shape of a cylinder. By using two asynchronous motors, one connected to each axis, the cleaning nozzle can move independently both horizontally and vertically. Feedback is obtained from two incremental encoders, for positioning and speed, and two inductive sensors used to identify the position of the nozzle at start (homing). A Human Machine Interface (HMI) is used for basic control and monitoring of the process.

The main focus has been on developing the algorithm but major time has also been spent on getting the hardware to function together to enable testing. By introducing a coordinate system and converting the coordinates, given by the user, to motor positions it is possible to create a pattern of cleaning points. Varying the output signals to the motors it is possible for both motors to reach the point simultaneously and keep a constant peripheral velocity of the jet beam. Tests were carried out on a test stand without cleaning fluid.

Rörelsestyrd tankrengöring

Ett examensarbete utfört av Mattis Wahlby, avdelningen för Industriell Elektroteknik och Automation, vid Lunds Tekniska Högskola


Figure 1: En tank i processmiljö

Föreställ dig följande scenario: Det är dags för veckostädning av din lägenhet. Du vet att det är smutsigast i hallen och skulle därför vilja lägga mest tid där. Men din rumskompis har bestämt att du måste lägga lika mycket tid i alla rum oavsett om det behövs eller inte. Låter det effektivt?

Samma problematik återfinns vid rengöring av stora tankar. I ett bryggeri måste en tank rengöras mellan varje sats liksom ett tankfartyg måste rengöra sina tankar inför nästa uppdrag. Med existerande rengöringssystem placeras ett rör, med ett munstycke i änden, i tanken. Munstycket fördelar sedan någon typ av rengöringsvätska, ofta vatten, på tankens insida tills den anses vara ren. För tankar med klibbigt innehåll används en jetstråle som med hjälp av en konstant rörelse hos munstycket skapar ett sprutmönster på tankens insida. Problemet uppstår när vissa delar av tanken är smutsigare än andra, likt lägenheten i ingressen. För att spendera mer tid där det behövs måste hela tanken rengöras under längre tid.

Det här examensarbetet fokuserar på att lösa problemet genom att göra det möjligt att anpassa sprutmönstret så att de delar av tanken som behöver mer rengöring får det, utan att hela tanken måste rengöras. Genom koppla en motor till varje rörelseriktning och låta en industri-PC (PLC) styra motorerna enligt ett mönster som skapas av användaren kan vilka sprutmönster som helst bildas.

Maskinen

Det rent mekaniska problemet har, i den här prototypen, lösts genom att modifiera en existerande rengöringslösning, Gunclean Toftejorg . Den fungerar på ett liknande sätt som prototypen (figur 2) men munstyckets rörelse drivs av en turbin som hämtar sin kraft från vattenflödet som används för rengöringen. Genom att modifiera växellådan och koppla en motor till varje rörelseriktning, horisontellt och vertikalt, ges möjlighet till styrning av munstycket, motion control.

En algoritm löser problemet

För att avgränsa problemet modelleras tanken som en perfekt cylinder. Ett koordinatsystem byggs upp från centrum av tanken i nivå med munstycket. Punkterna som bygger upp sprutmönstret definieras utifrån rotationsvinkel i horisontella planet (yaw vinkel), vertikalt och horisontellt avstånd till punkten från centrum av tanken. Genom att utnyttja grundläggande trigonometriska formler kan avståndet mellan munstycke och punkt beräknas, även om detta är placerat mitt i tanken.

Punkterna konverteras sedan till användbara värden för motorerna. Genom att beräkna hur många varv varje motor måste snurra kan man på förhand justera hastigheten på den motor som har minst antal varv att röra sig. Med minskad hastighet når båda motorerna, och därmed munstycket, punkten samtidigt både vertikalt och horisonellt. En "rät" linje skapas därmed mellan de två punkterna.

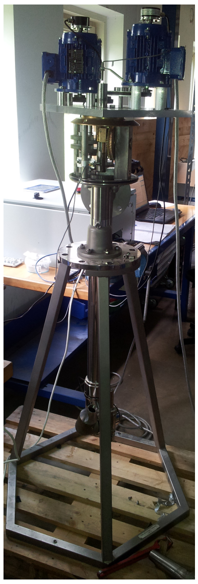
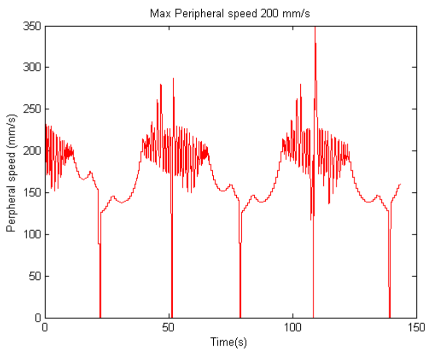


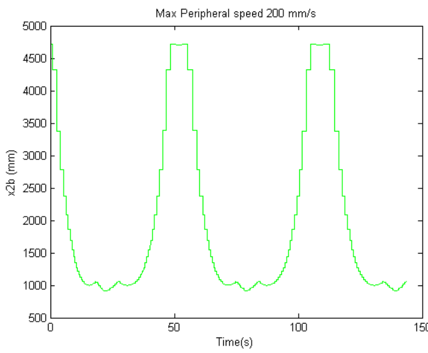
Figure 2: Gunclean Toftejorg. Högst upp syns motorerna ovanpå växellådan, längst ner syns munstucket som "ritar upp" sprutmönstret

Ett annat centralt problem är att jetstrålens hastighet, där den träffar tankens insida, varierar beroende på strålens längd. En konstant hastighet på munstycket kommer alltså inte att leda till en konstant s.k. perferihastighet. Detta löses genom att definiera en maximal perferihastighet och sedan hela tiden beräkna strålens nuvarande längd. Sedan beräknas den nuvarande perferihastigheten och jämförs med maxgränsen. Om den överstigs sänks den till en nivå som gör att den alltid hålls under maxgränsen.

Resultat



(a)



(b)

Figure 3: Variationer i perferihastighet jämfört med jetstrålens längd. Graferna visar processen under de fem första punkterna.

Figur 3 visar signalerna för jetstrålens längd samt perferihastigheten. Här har en maxgräns på 200 mm/s lagts till och det syns i figur 3a att hastigheten håller sig runt den gränsen. Variationerna beror på en otillräcklig reglering men märks endast när signalerna studeras, inte på den faktiska perferihastigheten. Om man jämför de två figurerna syns även att det är då jetstrålen är längre som maximal perferihastighet uppnås, medan perferihastigheten håller sig under maxgränsen för kortare avstånd. Detta beror såklart helt på vilken maxgräns som anges av användaren.

I framtiden finns stor potential för produkten. Med små förändringar i algoritmen kan tankar med andra geometrier rengöras och med en bättre reglering kan precisionen ökas ytterligare. Genom att använda detta system finns stora vinster att göra, både miljömässiga och ekonomiska. Kortare och mer effektiv tvättning leder till mindre energi och vattenförbrukning samtidigt som tanken kan komma tillbaka i drift snabbare.

Även om lösningen är bra kan du tyvärr inte använda den där hemma i lägenheten, i alla fall inte om du vill ha någon rumskompis kvar efter städningen.

Contents

Preface

This thesis constitutes the fulfilment for my degree of Master of Science in Engineering Physics at Lund University, Faculty of Engineering (LTH). It corresponds to 20 weeks of full time work and was performed in cooperation with Alfa Laval in Copenhagen through Core Automation Team (CAT) in Søborg and Alfa Laval Tank equipment in Ishøj. There are a number of persons I would like to thank for contributing to the project:

Peter Blomberg, Alfa Laval Søborg For introducing me to Alfa Laval in the first place and always being positive about the project and my work in general.

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Alfa Laval CAT, Søborg For sharing your time always answering my questions in a clear and informative way, you are the best!

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My friends and family For believing in me, and motivating me throughout my studies. Thank you!

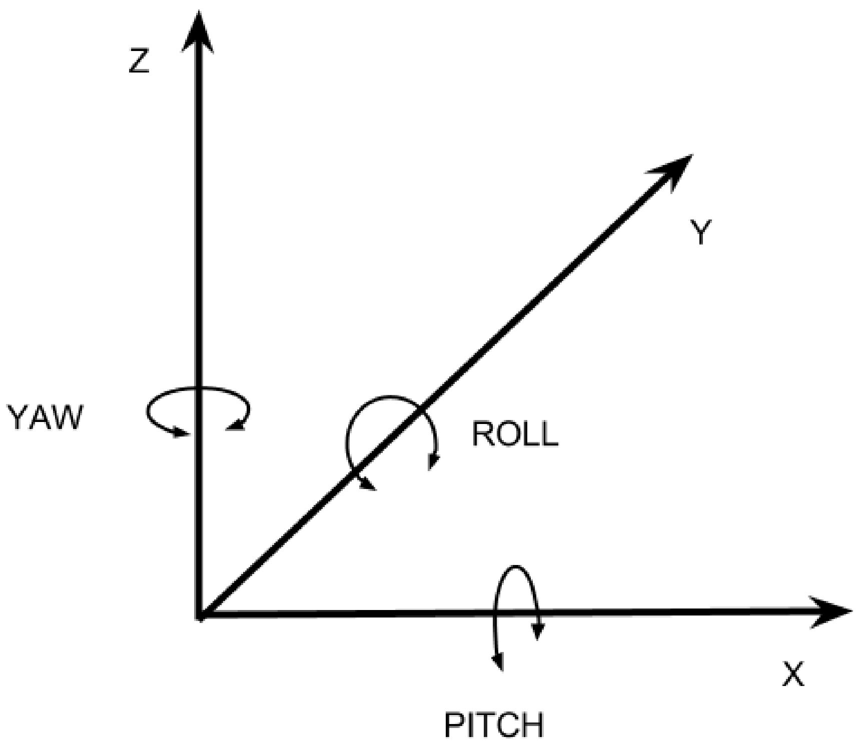
Malmö

Early fall 2013

Mattis Wahlby

Terminology

AS	Automation Studio, B&R Software for developing PLC programs.
B&R	Bernecker and Rainer, Austian automation company providing both hardware and software for automation solutions.
Beijer Electronics	Automation company with main focus on control panels and HMI solutions.
HMI	Human Machine Interface, a user interface that enable monitor and control of a process.
Homing	A procedure carried out at the start of a process, to know the positioning of the hardware.
iX Developer	Software provided by Beijer Electronics used for developing HMI.
Spray Pattern	A trajectory formed by a cleaning system.



Description of the angle movements

1

Introduction

1.1 Background

Improving the cleaning methods of large tanks may not only save time but energy and water and is therefore of great importance. Giving the user possibilities to create arbitrary spray patterns will prevent over excessive cleaning and at the same time creating an opportunity to focus the cleaning onto the most soiled areas of the tank.

Figure 1.1: Alfa Laval cleaning system [1]

There are several types of automated tank cleaning systems used today but the majority are using the same principle. The cleaning fluid is distributed trough a nozzle (seen in figure 1.1) on the inside of the tank until it is considered clean. The cleaning time has to be adjusted to the most soiled area since the whole tank is cleaned with the same intensity regardless of which areas that actually needs the most cleaning. This may cause longer downtimes than necessary since not all of the tank needs the same cleaning due to obstacles, special equipment etc.

When cleaning tanks used for brewing beer the walls of the tank are cleaned just by the water flowing down. It will save both time, water and energy to make the cleaning of such tanks more adaptive so that the cleaning fluid can be focused on the parts of the tank that gives the most effective cleaning.

A common solution for larger tanks, such as tanks used for crude oil and chemicals, is to have a stationary pipe going into the tank and place a nozzle on the end that will direct a high pressure beam of cleaning fluid to the inside of the tank. This type of beam will in the rest of this thesis be referred to as the jet beam. The motion of the jet beam in the tank will create a "pattern", referred to in this thesis as the spray pattern. It is possible to change the spray pattern of the tank by changing the design of the nozzle but the possibilities to control the process are limited.

This master thesis develops a modification of the Alfa Laval product "Gunclean Toftejorg" (seen in figure 2.5). It is a solution that makes it possible to create arbitrary spray patterns that will make the cleaning process more effective.

1.2 Scope

Alfa Laval provides several types of cleaning systems for large tanks. To enhance the cleaning process, improved control of the nozzle is demanded. For tanks within certain processes, e.g. dairy products and beverages, it is often enough to clean only the upper half of the tank. Therefore it would be beneficial to be able to create that type of pattern, while not making any changes to the hardware. Other tanks used for carrying crude oil and chemicals often have a maximum jet beam length of up to 40 meters. With that kind of distance the impact pressure is directly dependent of the angular speed of the nozzle. To keep the same impact when the length of the jet beam varies it is necessary to constantly adapt the speed of the nozzle.

1.3 Aim

The aim of this project is to modify the "Gunclean Toftejorg", referred to as the guncleaner, so that it can be used for position controlled cleaning. The main task here is to develop an algorithm for the cleaning process and an HMI so that the user may create spray patterns, control and monitor the process.

The implementation will be tested together with the motors to make sure that the goal is reached. Furthermore there will also be tests on a complete test stand with gearbox, pipe and nozzle.

1.4 Approach

The core of this thesis is the development of an algorithm for the motion control of the nozzle. The algorithm was developed from basic trigonometry together with specifications of the process, such as impact pressure and maximum peripheral speed.

Motion control tasks are commonly solved using stepper or servo motors to ensure precision. Since Alfa Laval did not see the need of high precision motors and due to several other factors such as price, robustness and Alfa Laval standards, common asynchronous motors with external encoders are used in this project.

Working with the B&R [2] software Automation Studio (AS) [3] many function blocks from motion control projects could be reused in the implementation of the algorithm. Theory on communication and how to connect the components have been available through manuals and data sheets.

The calculations and approximations as well as the algorithm are based on logical reasoning and simulations.

The work has been structured as follows:

- Investigation of the process

- Creating a model and an algorithm
- Implementation of the algorithm
- Testing

1.5 Disposition

This thesis will have the following disposition: Chapter 2 covers the theory needed to understand the process and the hardware. In chapter 3 the algorithm, approximations and calculations made are explained. Chapter 4 describes the solutions to the central problems and chapter 5 presents the results of the simulations and tests. The last chapter 6 concludes and discusses the results.

2
Theory

This chapter describes the most common spray patterns used [4] and the current cleaning solutions for large tanks within Alfa Laval. Most of these solutions are very similar to products from other companies in the sector, hence only cleaning systems from Alfa Laval are described here. A brief overview of all systems is given with the main focus on the guncleaner that is to be modified.

2.1 Spray patterns

The spray pattern is the trace of the jet beam in the tank. It can have different appearance depending on the nozzle design and movement. The purpose of the spray pattern is to clean as effective as possible with a minimum of time and water being used. This section will describe the most common spray patterns used by companies today.

2.1.1 Film

With this method the nozzle delivers a thin film of water equally distributed over the inside of the tank. The water then flows down along the walls and cleans the tank. This is not a jet beam pattern and is used to clean tanks with non sticky contents.

2.1.2 Helical pattern

This is the pattern used by most Alfa Laval cleaning systems using a jet beam. It is obtained by a constant rotation of the nozzle around the vertical axis (yaw) while slowly changing the angle of the horizontal axis (pitch). This results in a cleaning pattern seen in figure 2.1.

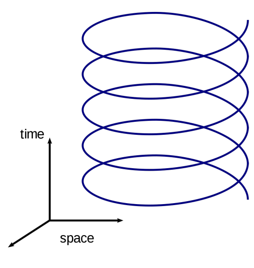


Figure 2.1: Helical pattern [5]

2.1.3 Criss Cross pattern

With several nozzles the spray pattern is slightly different since the pitch angle changes faster.

Each cleaning cycle is slightly displaced from the previous to reach full coverage of the tank after about four cycles, depending of the size of the tank see figure 2.2. After several cycles this leads to a criss cross pattern.

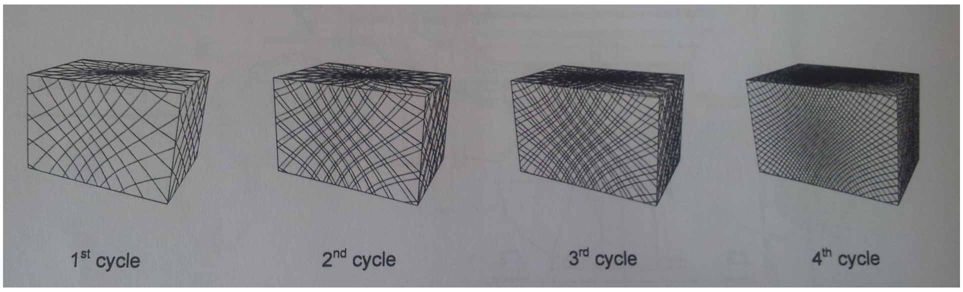


Figure 2.2: Crisscross pattern created with multiple nozzles [6]

2.2 Mechanical solutions

This section briefly describes the most common cleaning systems within Alfa Laval. Since the aim of the project is to modify the guncleaner it is described in more detail.

2.2.1 Rotary spray ball

This is the, motion wise, most basic type of automated cleaning [8]. A pipe is introduced into the tank, often from the bottom or top. At the end of the pipe there is a spherical nozzle. The nozzle is designed with holes and gaps so that when the high pressure water flows through, the nozzle starts to rotate. Depending on how the holes on the nozzle are configured it is possible to get a peripheral impact on all of the inside of the tank. The solution delivers both impact pressure and also covers the tank with a thin film of rinse water flowing down.

Figure 2.3: A spray ball nozzle [7]

This solution is very easy to mount and only needs very limited service. On the other hand it is not possible to create advanced spray patterns and the pressure of the jetbeam is limited which makes this a solution for tanks with less sticky rest products.

2.2.2 ISO mix

The ISO mix system [9] is primarily used for mixing in powders and fluids into the tank but can also be used for cleaning. When used for cleaning it works similar to the spray head but delivers a criss cross pattern seen in figure 2.2. The main difference from the rotary spray ball is that the yaw rotation is created from the water pressure via a turbine, placed outside the tank together with a gearbox and a magnetic brake to obtain the desired speed. The actual nozzle consists of two or four openings see figure 2.4. The pitch rotation is conceived from pressure of the jet beam.

Figure 2.4: ISO mix, nozzle with four openings [9]

2.2.3 Guncleaner

The guncleaner [10] (see figure 2.5) is a powerful cleaning solution that directs all the water through one opening in the nozzle with an inlet pressure ranging from 5 to 12 bar. The high pressure delivers a jet beam that can reach distances of 40m, still retaining the impact pressure. It is primarily used for tanks that contain sticky substances such as crude oil and chemicals.

Function

Since the guncleaner only has one opening in the nozzle there will be no controlled pitch angle movement from the pressure of the jet beam. Instead both the pitch and yaw angle movement is dealt with as the yaw angle movement in the ISO mix system. A turbine together with a gearbox is placed outside the tank and converts the rotations of the turbine into useful angle speeds by the gearbox.

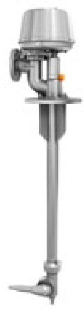


Figure 2.5: The latest version in the "Toftejorg series", i40 s [11] [12]

The gearbox is connected to a rod placed inside the water pipe in the tank. Rotation of the rod results in a yaw movement of the nozzle whereas elevation results in a pitch movement. The pitch movement is possible through racks in both ends of the rod and limits the pitch angle to 180 degrees. The yaw movement is delivered from the gearbox via a magnetic clutch that can also be used to change the yaw angle speed.

The guncleaner performs a helical pattern with some possibilities of adjustment. The vertical density of the pattern may be changed, even during cleaning, between four different “programs”. The difference between the programs is the change of pitch angle for each yaw revolution. A small change will result in a denser pattern but it will take longer to finish the cleaning cycle since one cycle defined as the pitch angle changing from 0 to 180 degrees. The yaw angle speed is normally kept at 60s per revolution depending on the size of the tank. This number has been obtained empirically after many years of testing.

Limitations

The main limitation of the guncleaner is that the yaw and pitch movements are connected to the same power source, the turbine. Depending on the program and the gearbox settings, such as the number of pinions and the size of the rack wheels the pattern can be adjusted. Nevertheless the nozzle will always move in both yaw and pitch angle at the same time and direction and the movement will be depending of the pressure of the inlet water, higher inlet water makes the nozzle move faster.

Another limitation is that the horizontal rotation is always moving in the same direction which makes it impossible to create spray patterns that follow arbitrary trajectories, as needed when cleaning a specific area.

The vertical motion may be varied with a programming knob that gives four different options on how many degrees the pitch angle should change for every full horizontal lap. The pitch angles for start and stop of the process are chosen before the cleaning starts but may be changed during the process.

Pattern and impact velocity

The guncleaner does not make any adjustments in angle speed depending on the distance from the nozzle to the object. Instead an average length to the walls is used and the yaw angle speed is adjusted so that a sufficient impact pressure is delivered. The impact pressure is also depending on the diameter of the nozzle and the inlet water pressure. No studies have been done on how much the jet beam bends at high movement speeds, but in this project the jet beam is considered to be straight.

2.3 Hardware

The following section briefly describes the hardware used in this project.

2.3.1 Gearbox

The gearbox is of standard, turbine powered type, used with most models of the guncleaner. The two axis have been "unlocked" so that they may move independently from one another. In figure 2.6 the gearbox with the two motors mounted can be seen.

2.3.2 Motor

Two Marelli [13] asynchronous motors with a rating of 0.73 kW are used in this project. the size of the motors are dimensioned to function with the gearbox current outline. With less gears more powerful motors should be considered. The motors are equipped with external cooling but since this project is only running a few short cleaning cycles there is no need for that kind of cooling at this stage of the project.

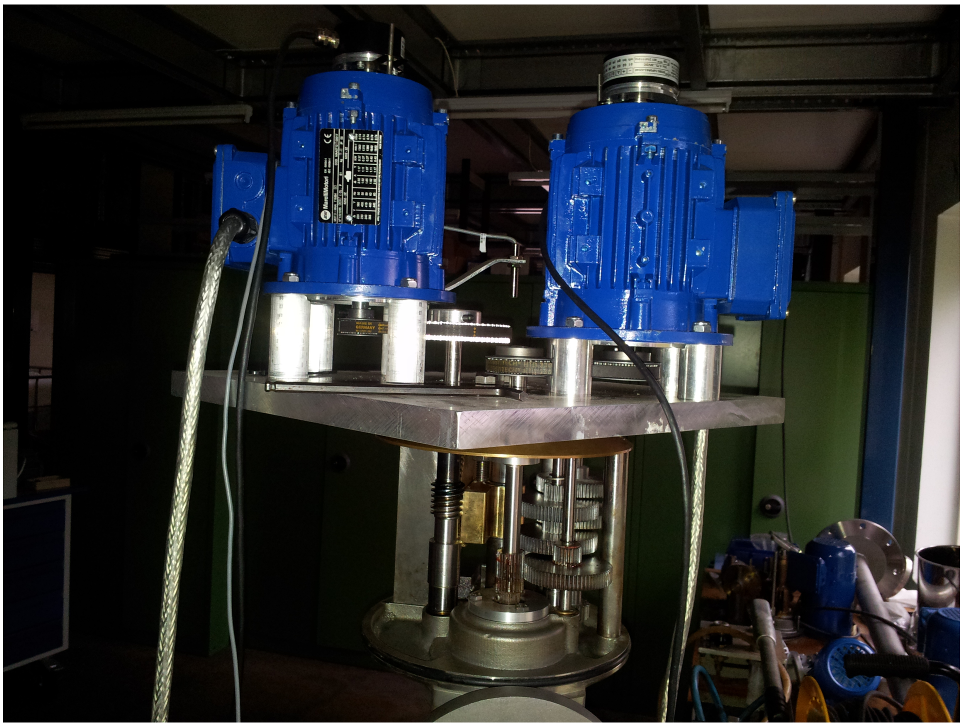


Figure 2.6: The two motors mounted on top of the gearbox

2.3.3 Variable Frequency Drive

The variable frequency drive (VFD) used in this project is delivered by ABB [14]. A VFD is used to control the speed of an electrical motor by changing the frequency input to the motors. A positive and negative frequency will result in a change of rotational direction for the motor. The frequency may be varied from zero (standstill) to 50 Hz (Full speed). In figure 2.7 the two VFD's can be seen. Mounted on the front are two external modules for communication with the PLC via Powerlink, described in section 2.4.2.

Figure 2.7: The VFD's with mounted external modules

2.3.4 Programmable Logical Controller and modules

The Programmable Logical Controller (PLC) used in this project is the B&R standard PLC X20-1484 [15]. It is used as standard platform within Alfa Laval. To handle the signals from the sensors, encoders and emergency stop there are three I/O modules [16] connected to the PLC. One for digital input signals, one for digital output signals and one for counting the pulses from the encoders. The communication between the PLC and the VFD is done via Ethernet Powerlink [17] (EPL) which is a communication standard developed by B&R using standard Ethernet cables.

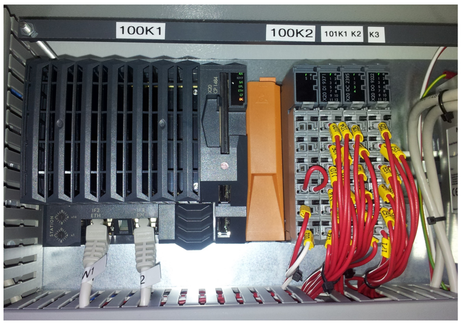


Figure 2.8: The PLC and I/O modules

2.3.5 Sensors and encoders

Two rotational incremental encoders from Global encoders [18] are used to measure position and speed of the motors. The encoders were mounted directly on the motor axis and the actual position of the nozzle was calculated using the algorithms in chapter 3.

The proximity sensors, delivered by Pepperl-Fuchs [19], where used for the homing process, described in section 4.2.3. This section also describes the placement of the two sensors in the gearbox. In this application inductive sensors are used since there were suiting metal components in the gearbox that could be used to get a good signal.

2.3.6 Control panel

To control the process the Alfa Laval standard 7" panel is used. It is delivered by Beijer Electronics [20] and contains the basic Human Machine Interface(HMI) described in section 2.4.1.

2.4 Software and Communication

In this section the communication protocols, software and HMI will be described.

2.4.1 Human Machine Interface

The HMI is developed with the software iX Developer [21] from Beijer Electronics. It follows the Alfa Laval standard 2 Touch [22] which is a intuitive way to control and monitor a process with simple reach of all functionality.

All screens in the HMI can be reached with just two touches from the user, hence the name 2 touch.

2.4.2 Ethernet Powerlink

In this type of project the communication between the PLC and the VFD is normally done via I/O interface. This means that an input/output signal from the VFD is transmitted to an I/O module on the PLC and handled as a normal input/output signal. In this project however it was decided that B&R's own Ethernet protocol, Powerlink was to be used.

Compared to a normal I/O interface using Powerlink enables more information from the VFD to be transmitted and used by the PLC. At this stage of the process the necessity is not crucial but it might be with future applications. The communication is done via ordinary RJ-45 cables via a specially made connection card provided by ABB. The card allows several VFD's to be daisy chained [23] as is the main idea with the Powerlink interface. When using daisy chaining only one connection to the PLC is needed instead of one for every VFD.

2.4.3 ABB interface

The communication protocol used is the ABB standard protocol provided in the manual [24]. It is an overlayer to Ethernet Powerlink and relies on a control word and a status word consisting of a 16-bit integer each. The status word provides data from the VFD, current working mode for example. With the control word data is transmitted from the PLC to the VFD.

Furthermore a reference signal reaching from -32768 to 32767 is sent from the PLC where the minimum value represents full speed counter clockwise and the maximum value means full speed clockwise direction of the motor. A reference-status signal of the same type is sent from the VFD containing the actual speed of the motor.

2.4.4 OPC-server

OPC is a standard for communication between different computers, including embedded systems [25]. It was used to handle the communication between the PLC-software and the HMI-software. An OPC-server was established and all the parameters needed in the HMI was put in a special list of variables and converted for use in the interface of the HMI-software. The important variables here are the coordinates and the start, stop, pause functionality together with the current position of the nozzle.

3 Algorithm

The algorithm is based on basic trigonometric functions such as the law of cosines, the law of sine and the Pythagoras' theorem [26]. To facilitate for the user, when picking the coordinates, the angles and distances use the centre of the tank in the plane of the nozzle as reference point.

To convert the input values to motor positions a transformation needs to be done. Using trigonometry the input angles can be changed into motor angles and, by multiplying with a compensation factor for the gearbox, into motor positions.

3.1 Approximations

The form of a tank used within the dairy industry can be seen in the picture below. To facilitate calculations the tank is considered to be a perfect cylinder and the jet beam is assumed not to bend between the nozzle and the point of impact. This approximation affects the top and bottom but the jet beam will still reach these areas and the change of coordinates for those are minor.

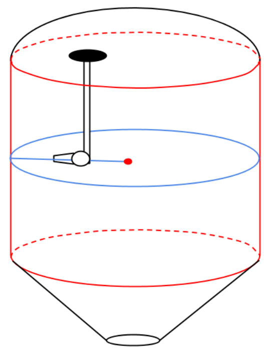


Figure 3.1: Approximation of the tank

3.2 Calculations

The following sections explain the calculations made both to convert the input parameters to motor angles and to know the current position and length of the jet beam.

3.2.1 Angle to position

The purpose of the following calculations is to use the known parameters to calculate the yaw angle of the motor. Since the triangle will have a different appearance for 0 to 180 degrees compared to 180 to 360 degrees there will be two types of calculations. Even though they are very similar both are shown

for clarity. As seen in figure 3.2 the yaw angle is called β.
The known parameters are:

a_c - the distance from the centre to the nozzle
r - the radius of the tank which here coincides with d_r
d_r - the distance from the centre of the tank to the impact point
α - the yaw angle from the centre of the tank

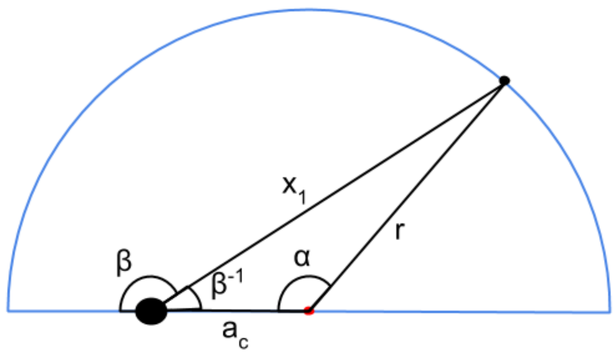


Figure 3.2: Distance from nozzle to wall (x_1) in the horizontal plane of the nozzle

The following calculations are made from 0 to 180 degrees. First the distance from the nozzle x_1 is calculated.

$$x_1^2 = a_c^2 + d_r^2 - 2a_c d_r \cos(\alpha) \tag{3.1}$$
$$x_1 = \sqrt{a_c^2 + d_r^2 - 2a_c d_r \cos(\alpha)} \tag{3.2}$$
$$\beta^{-1} = \arccos\left(\frac{a_c^2 + x_1^2 - d_r^2}{2a_c x_1}\right) \tag{3.3}$$
$$\beta = 180 - \beta^{-1} \tag{3.4}$$

Then from 180 to 360 degrees.

$$x_1^2 = a_c^2 + d_r^2 - 2a_c d_r \cos(360 - \alpha) \tag{3.5}$$
$$x_1 = \sqrt{a_c^2 + d_r^2 - 2a_c d_r \cos(360 - \alpha)} \tag{3.6}$$
$$\beta^{-1} = \arccos\left(\frac{a_c^2 + x_1^2 - d_r^2}{2a_c x_1}\right) \tag{3.7}$$
$$\beta = 180 + \beta^{-1} \tag{3.8}$$

To calculate the pitch angle of the motor γ the distance from the nozzle to the impact point in the nozzle plane x_1 is used together with the known parameter d_z that gives the vertical distance between the nozzle plane and the impact point. First the distance from the nozzle to the impact point x_2 is calculated by Pythagoras' theorem and is then used to get the pitch angle γ

$$x_2 = \sqrt{x_1^2 + d_z^2} \tag{3.9}$$
$$\gamma = \arccos\left(\frac{x_1^2 + x_2^2 - d_z^2}{2x_1 x_2}\right) \tag{3.10}$$

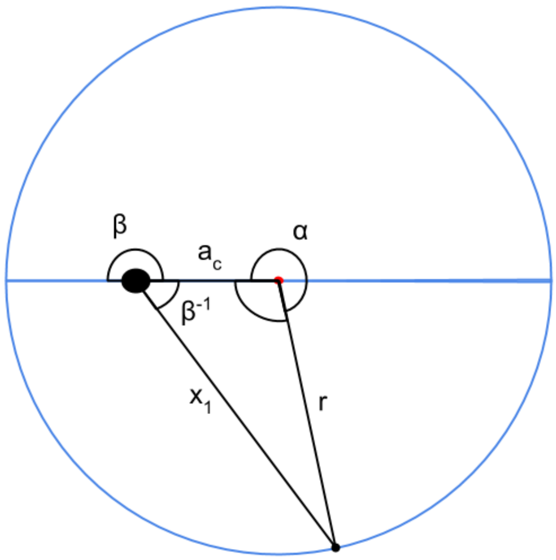


Figure 3.3: Distance from nozzle to wall (x_1) in the horizontal plane of the nozzle

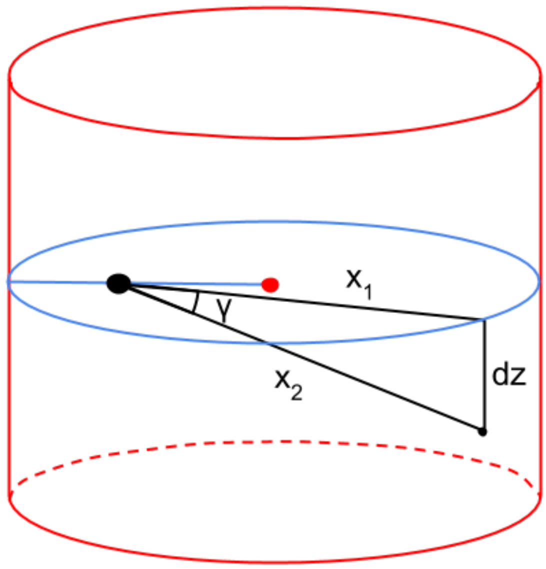


Figure 3.4: Distance from nozzle to point (x_2)

When the impact point is on the bottom of the tank Pythagoras' theorem is used once more but this time with the distance from the nozzle plane to

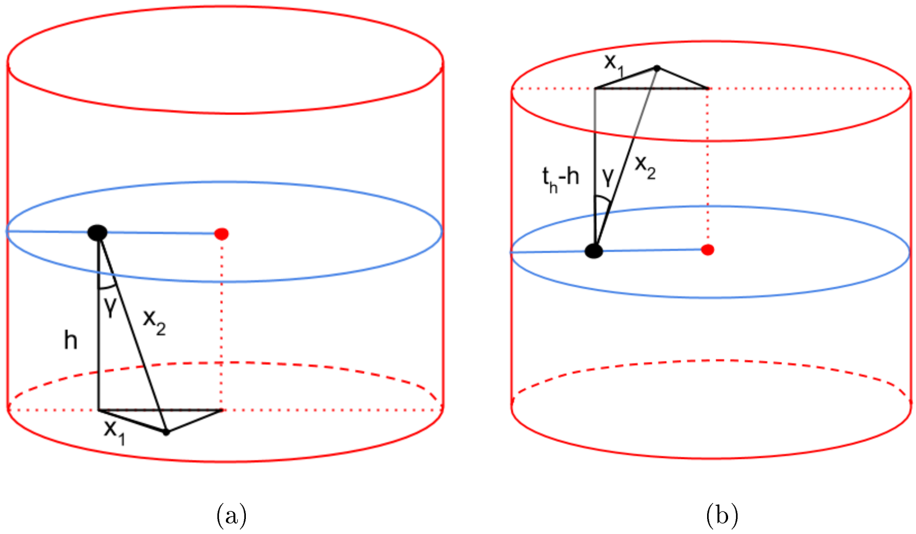


Figure 3.5: Distance from nozzle to the impact point (x_2). Impact point on the bottom, 3.5a, and top, 3.5b of the tank.

the bottom of the tank h.

$$x_2 = \sqrt{x_2^2 + h^2} \tag{3.11}$$

$$\gamma = \arccos\left(\frac{-x_1^2 + x_2^2 + h^2}{2x_2 h}\right) \tag{3.12}$$

The pitch angle of the motor γ is calculated in a similar way when the impact point is situated in the top of the tank, using the tank height t_h.

$$x_2 = \sqrt{(t_h - h)^2 + x_1^2} \tag{3.13}$$

$$\gamma = \arccos\left(\frac{-x_1^2 + x_2^2 + (t_h - h)^2}{2x_2(t_h - h)}\right) \tag{3.14}$$

3.2.2 Position to angle

To maintain the constant peripheral speed of the jet beam one is interested in knowing the current length of the jet beam. Knowing the length and towards which surface the jet beam is directed it is possible to adjust the speed of the motors depending of the length of the jet beam to get a constant impact.

The problem here is that the only available parameters are the yaw and pitch angles connected to the two motors. That information is not sufficient to know if the impact point is situated on the wall, top or bottom of the tank. Therefore the limit between wall/top and wall/bottom was pre calculated for 3600 yaw angles ranging from 0 to 360 degrees. Provided this additional information it is possible to know which pitch angles that results in an impact point on the top or bottom for a specific yaw angle.

3.2.3 Nozzle compensation

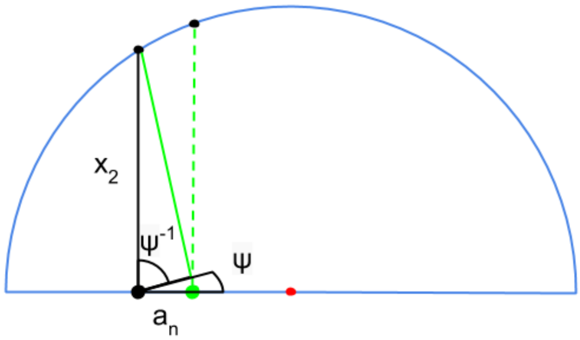


Figure 3.6: Compensation angle ψ for the horizontal nozzle offset

Since the nozzle is not situated at the centre of the pipe, see picture 3.6, there will be a horizontal offset of the impact point. The distance from the centre of the axis is marked n_a and it is this distance that gives the offset. The following equations are used to compensate the horizontal angle ψ:

$$\cos(\psi^{-1}) = \frac{a_n}{x_2} \tag{3.15}$$

$$\psi^{-1} = \arccos\left(\frac{a_n}{x_2}\right) \tag{3.16}$$

$$\psi = 90 - \psi^{-1} \tag{3.17}$$

4
Implementation

4.1 Program structure

The program structure is based on three major programs, and two minor for the SDC axis that handles the communication with two axis-objects (gAxis01, gAxis02). Each of these objects is directly connected to a VFD controling the speed and direction of the motor.

Every program consists of several subprograms according to Alfa Laval standards. The following are the ones of central value to this project.

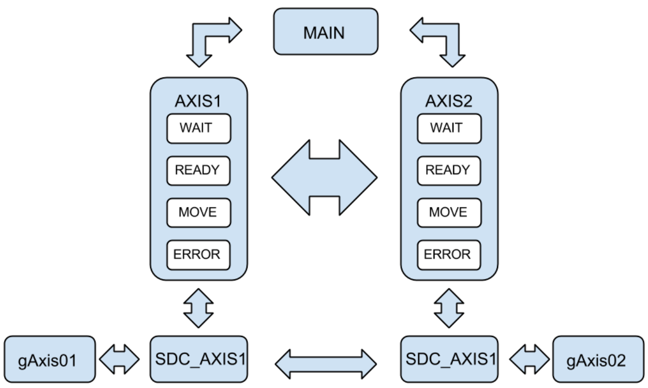


Figure 4.1: Structure of the program

Main Init This code is executed once when the program starts up.

Main Cyclic This is the actual program with the main features and functionality.

Sequence This Sequential Function Chart (SFC) handles the states.

Sequence Code Contains the code necessary for the state sequence of the program.

4.1.1 Main

The main program is responsible for the communication with the sub programs AXIS1 and AXIS2 but also with the HMI.

If a start signal is enabled by the user the angles and distances, defining the points that build the cleaning pattern, are converted to the correct angles for the motors. The points are placed in three arrays for use in the Axis1 and Axis2 programs respectively.

The distance from the nozzle to the wall is here calculated and the peripheral speed of the jet beam adjusted to a level within certain limits.

4.1.2 AXIS1 and AXIS2

These programs keep track of the current state of each axis-object. When started it performs homing, see section 4.2.3, and prepares the next movement so that the desired coordinates are reached at the same time for both motors. That is done by calculating the next movement and comparing this value with that of the other axis-object. The speed of the object with the shortest movement is scaled so that the nozzle reaches the target position at the same time both for the pitch and yaw movements. When the position is reached a counter increases to keep track of the current position and number of cycles finished.

If the pause button is pressed on the HMI the motors are stopped and the current movement will be continued when the pause button is disabled.

The stop button can only be activated if the motors are first paused. If it is activated then the whole process is reset and the axis will start over when the start signal is enabled.

The movement used is a function block called “moveadditive” depicted as MOVE in figure 4.1. When active and no errors are detected the program switches between the ready state and the "moveadditive" state. If an error occurs the process will end up in the "erroraxis" state and will only return to the ready state if the errors are acknowledged. All errors are automatically generated by the axis-object e.g. in case of a lag error or signal error.

4.1.3 Smart Device Controller (SDC)

The SDC is a controller developed to make it easier to design motion control tasks. It has predefined ramp functions and control algorithms. The SDC is connected to the axis-object and works as a link to connect the input signals from modules and sensors to the program.

4.2 Solutions

This section will focus on the central parts of the task and how the different challenges have been solved.

4.2.1 Handling coordinates

When developing the algorithm a coordinate system is introduced. The coordinates are given in a yaw angle α, a vertical distance from the horizontal plane of the nozzle d_z and a horizontal distance from the vertical plane of the nozzle to the point of impact d_r. These three values need to be converted to useful positions for the motors, i.e. a pitch and a yaw angle.

The following flowchart in figure 4.2 describes the code executed in MAIN. It converts the three values α, d_z and d_r into yaw and pitch angle, β, γ, that is sent to AXIS1 and AXIS2. Depending of the values of α and d_z different calculations are made according to section 3.2.

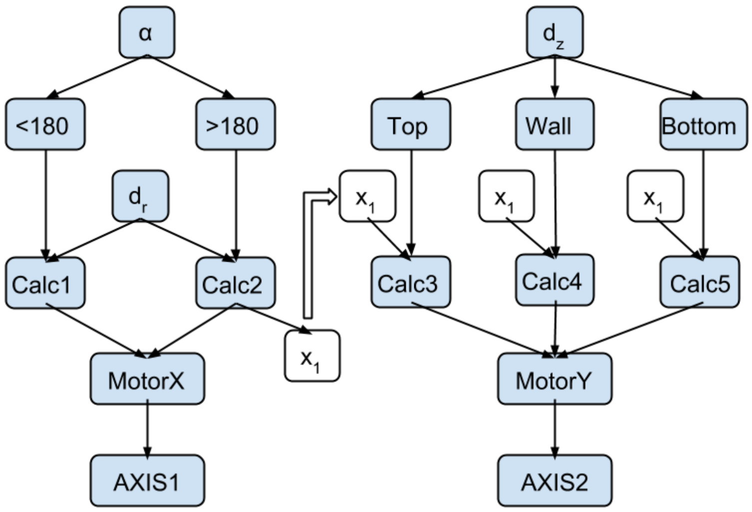


Figure 4.2: Converting the coordinates into motor angles

4.2.2 States

The process follows a state sequence governing the order of execution of the code. The structure of that sequence can be seen in figure 4.3. Here the error states for the axis programs, that can be reached from any state in the program, has been left out to make the diagram easier to follow. In figure 4.3 one may also see how the user can control the process in real time using the START, PAUSE and STOP commands from the HMI. The STOP command will terminate the process and may only be enabled when in the state HALT.

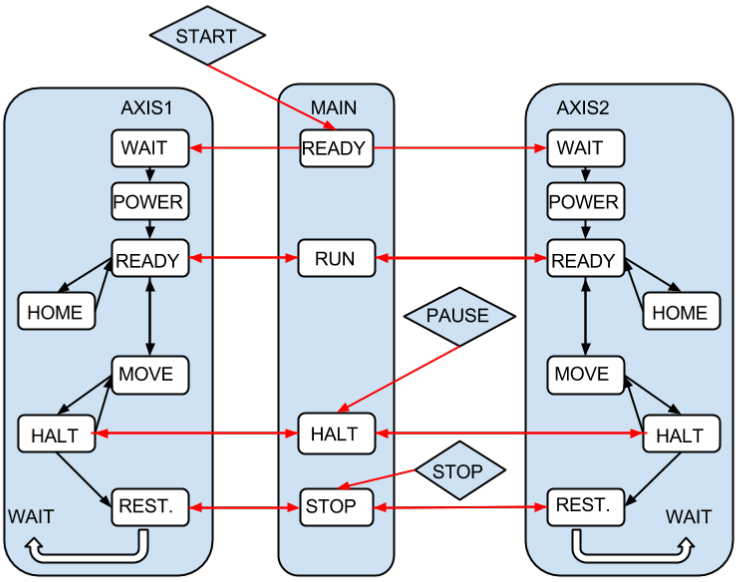
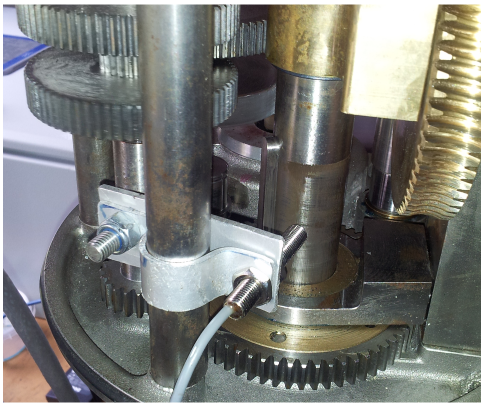


Figure 4.3: Overview of the states in the process, red arrows showing external commands



(a) Yaw angle sensor

(b) Pitch angle sensor

Figure 4.4: Placement of the inductive homing sensors

4.2.3 Homing

When the process is started the nozzle is pointing in an unknown direction. An operation called homing is therefore carried out before initiating the cleaning pattern. During the homing operation the motors will move until the homing sensors are activated, see figure 4.4.

When searching for the home position both motors are always moving in the same direction to make sure that the position is accurate. The inductive sensors respond to a proximity to metal. Therefore the pitch angle sensor is placed so that when the rod is at the top position (with the nozzle pointing straight up) the sensor is activated. The yaw angle sensor is activated by a heel on the rotating rod.

4.2.4 Constant peripheral speed

A crucial function in this project is that, independent of the distance to the impact point, the peripheral speed is kept constant. In order to implement this it is necessary to know the current distance from the nozzle to the impact point to be able to adjust the speed.

Since the only information given is the pitch and yaw angles of the motors, the length of the jet beam has to be calculated from that. The pitch angle, however, does not give any information on if the impact point is currently on the wall, bottom or top of the tank. To handle this the limits between the wall and bottom and wall and top are pre calculated for 3600 angles reaching from 0 to 360 degrees. With this information it is possible to know on which surface a given pitch angle places the impact point. Using the calculations in section 3.2.2 the distance from the nozzle to the impact point is known.

Predefined limits decide the maximum peripheral speed which is compared to the current speed and length of the jet beam. If the speed is too high the speed signal to the motors is overridden and lowered to a value within the allowed range.

4.2.5 Synchronized movement

If the distance to the next point differs between the yaw and the pitch motor then one motor will reach the desired angle before and this will greatly affect the spray pattern. Therefore the distance to the next point is calculated and the values are compared between the motors. The motor with the shorter distance, the yaw motor in the equation below, will move with reduced speed.

$$yawspeed \quad = \quad yawnextmovement * \frac{pitchspeed}{pitchnextmovement} \tag{4.1}$$

4.2.6 Gearbox compensation

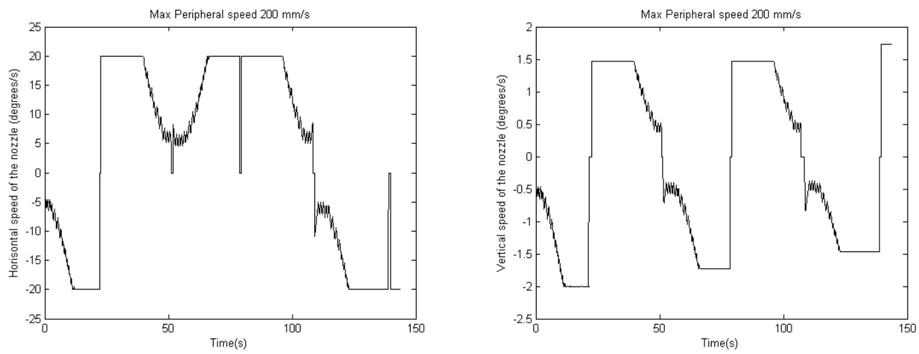
The gearbox used with this prototype is not optimized for the motors. Instead the same gearbox as for the turbine powered process is used. The only difference is that the two axis are not connected to the same power source.

By manually measuring the motor rotations for a known angle it is possible to obtain the gear/angle ratio. That ratio together with a load compensation is used for calibration of the process. With this gearbox configuration the pitch motor is running at very low speed compared to the yaw motor which is not optimal.

5
Results

The following chapter shows the results of crucial features, i.e. the synchronized movement and constant peripheral speed, together with the design of the HMI.

5.1 Synchronized movement



(a) (b)

Figure 5.1: The velocity of the nozzle in the horizontal and vertical directions

This section shows that both motors reach the point at the same time, where the speed is zero. As can be seen in figure 5.1 both motors reach the point simultaneously.

5.2 Constant peripheral speed

The following section presents the results of the tests done with different limit of the maximum peripheral speed. The tank size is constant and the spray pattern is shaped as a W, going from minimum to maximum in pitch angle and changing 60 degrees in yaw angle.

As can be seen in figure 5.2 the peripheral speed is varying, this i due to a bad regulator. There is a delay in the system resulting in that the actual

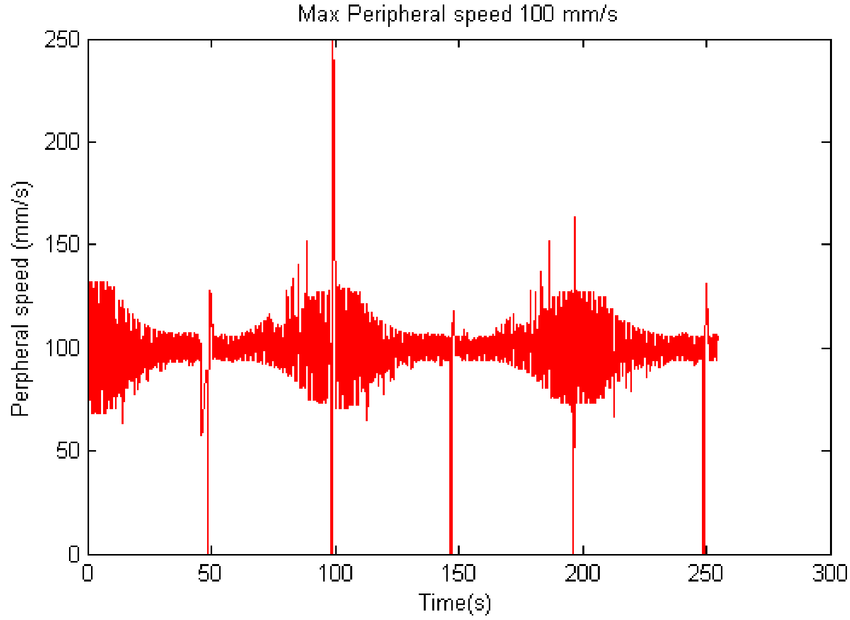
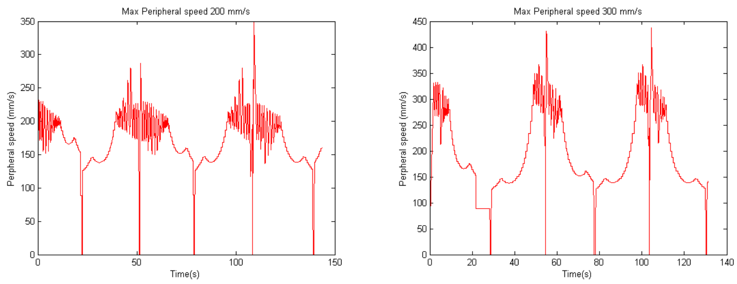


Figure 5.2: The peripheral speed is varying around 100 mm/s

speed of the nozzle is not following the the rapid fluctuations of the velocity signal.



(a)

(b)

Figure 5.3: Peripheral speed with limit 200 and 300 mm/s respectively

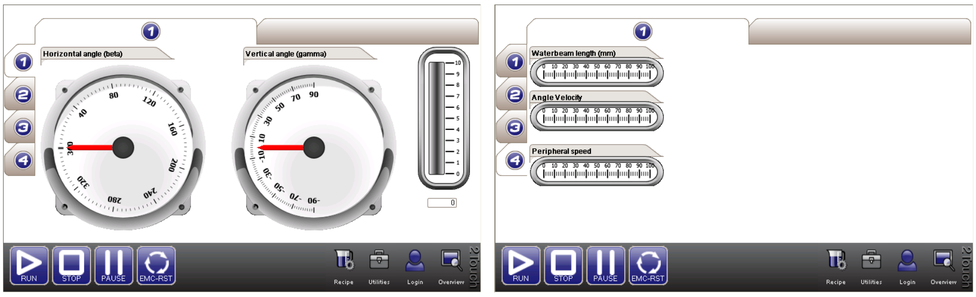
When the speed limit is raised, one can see that the top values stay around the limit as seen in figure 5.3.

5.3 Human Machine Interface

The basic HMI developed for control and monitoring of the process consists of four different screens. In the bottom part of every screen is a control bar where the user may start, stop and pause the process.

On the main screen, figure 5.4a, the angle of the nozzle is monitored along with the current point and the number of cleaning cycles.

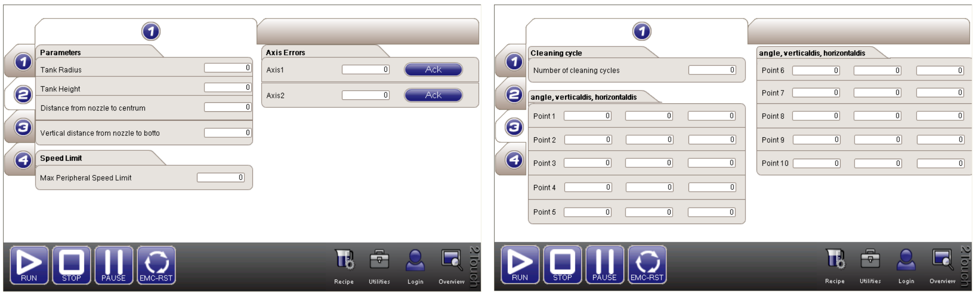
The monitor screen, figure 5.4b, contains three bars describing the current angle velocity together with the length of the jet beam and the current



(a) Main screen (b) Monitor screen

Figure 5.4: HMI screens for monitoring the process

peripheral speed.



(a) Parameter screen (b) Coordinate screen

Figure 5.5: HMI screens for input of parameters

On the parameter screen, figure 5.5a, the user can put in the size of the tank e.g. radius height and nozzle placement. Here it is also possible to set the maximum limit for the peripheral speed and to acknowledge errors on the axis.

The coordinate screen, figure 5.5b, enables the user to define the spray pattern by choosing ten points that will form the pattern. The coordinates are defined from the centre of the tank at the vertical level of the nozzle. One point is made up by three values according to section 3.2.

6 Experiences and Conclusions

In this thesis an algorithm has been developed and implemented to enable adaptation of spray patterns for large tanks. In this chapter the results are summarized and discussed. It also contains suggestions on further improvements.

6.1 Summary

Considering the limitations of the spray pattern in the original version of the Guncleaner, the focus of this thesis was to enable the possibilities of an arbitrary spray pattern with a constant peripheral speed of the impact point of the jet beam.

To solve this problem a coordinate system of the tank was created according to chapter 3. The tank was approximated with a perfect cylinder where the nozzle might be located at any given position in the tank, assuming that the pipe is pointing from the top of the tank and down.

To ensure that the peripheral speed was kept at a constant value the signals to the motors were overridden. In this way a change in length of the jet beam would change the output signals to the motors to keep a constant peripheral speed.

The hardware used in the project, e.g. motors VFD's and gearbox, was chosen due to the configurations of the original Guncleaner setup and were not optimized for the task. The communication between the VFD's and the PLC was done via Powerlink to prevent time consuming installations and reduce complexity of a future product based on this project.

Implementation of the algorithm was made with the B&R software Automation Studio in the language Structured Text. Special attention was put into the homing of the process and calibration of the program to coincide with the outline of the gearbox. The accurateness of reaching the predefined coordinates are satisfactory and show that the algorithm is fully functional. Tweaking the regulators would improve the accuracy.

6.2 Discussion

When first presented to the project it seemed pretty straight forward to develop and implement an algorithm of this type. Since there is only two degrees of freedom and two motors the problem lack the complexity of many other motion control problems. The development of the algorithm was very straight forward regarding that the tank was approximated with a perfect cylinder and the trigonometric used are of the basic kind. The difficulties in this project has instead been on the implementation and hardware side.

Working with a prototype has brought several factors in to this project that was not foreseen at the start. The communication with Powerlink between the PLC and the VFD's delivered by ABB had not been tested in any other project before. That lead to several weeks delay of the project since there was trouble with the external module converting the signals with the Powerlink protocol to the ABB standards. Furthermore the Alfa Laval standard motor supplier could not deliver motors well suited for this task. This led to the order of another brand that at delivery was faulty and had to be sent back for readjustments.

Looking back it might have been a wise decision to skip the implementing part of the project and focus on the development of the algorithm and perhaps creating models for several tanks of different shapes and just running simulations to check validity.

Considering that one of the goals with the project was to keep a constant peripheral speed the "override" solution worked well. As can been seen in the plots of chapter 5 the speed of the motors follows the variation of the maximum peripheral speed.

The accuracy of the nozzle is depending, not only on the software, but knowing the properties of the hardware. Since the gearbox was only modified to be able to work with the two electrical motors instead of the turbine, it was not optimized. This leads to that with this setup the motor controlling the yaw angle is working at higher RPM than the motor governing the pitch angle. In discussion with Alfa Laval it was made clear that millimetre precision was not needed and the motors used are not normally used for motion control projects.

6.3 Future work

This prototype only covers the basic functionality one can expect. For further development it is important to remember that the safety emergency stop system has not been implemented. That together with additional debugging and more testing are needed to ensure a stable and constant performance. No test has been done in an actual tank with water. It is possible that some changes needs to be done to the load constants due to the force of the jetbeam.

Considering that this prototype may only handle tanks of cylindrical shape modifications of the algorithm need to be done to handle tanks with other shapes.

The HMI interface only contains very basic features and needs improvement both graphically and otherwise. The HMI-communication may also be implemented in the Automation Studio interface in a more clear manner.

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