

Optimisation of Robot Picking Using Machine Vision

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Bachelor Thesis for Bachelor of Engineering

Degree Programme in Industrial Engineering and Management

Vaasa 2024

EXAMENSARBETE

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Titel: Optimering av robot med hjälp av maskininlärning

Datum: 6.11.2024 Sidantal: 38

Abstrakt

Detta arbete har gjorts på uppdrag av ABB Smart Power. ABB tillverkar olika typer av belastningsbrytare, brytningssäkringar och omkopplare. Brytarna används främst för solkraft, industriell strömföring och för att säkra strömtillförseln.

Examensarbetets syfte var att ta reda på om man kunde få en av deras produktionslinjer att fungera effektivare och smidigare genom att ändra på kalibreringsprocessen för en robots kamera, vid en specifik produktionslinje.

Denna specifika robots syfte är att plocka upp skal som är ramar för brytarna. Roboten plockar delarna ur en kartong låda där det finns många skal. Ibland händer det att roboten inte lyckas träffa rätt när den skall plocka upp komponenterna vilket i så fall leder till ett avbrott i produktionen.

Roboten använder en kamera för att se var delarna är och kameran tar en bild varje gång en komponent har plockats upp ur lådan. På det sättet vet roboten och ser vilken komponent som har plockats upp och vilka som är kvar i lådan. Genom att göra kalibreringsprocessen för kameran som roboten använder mer effektiv kan man minska på avbrotten i produktionen.

Genom att analysera kalibreringsprocessen för robotens kamera kunde sedan en alternativ kalibreringsprocess testas som visade sig vara mera lämplig eftersom den sparade in på tiden det tog att kalibrera kameran. Denna process gör det också lättare för personen som övervakar produktionslinjen att kalibrera kameran vid behov.

Språk: engelska

Nyckelord: maskininlärning, optimering, kalibrering, automation

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Päivämäärä: 6.11.2024 Sivumäärä 38

Tiivistelmä

Tämä opinnäytetyö tehtiin ABB Smart Powerille Vaasassa. ABB valmistaa erilaisia kytkimiä kuten kuormakytkimiä, kytkimen sulakkeita ja vaihtokytkimiä. Kytkimiä käytetään enimmäkseen auringonsähkössä, teollisessa virransyötössä ja virransyötön turvaamisessa. Opinnäytetyön tarkoitus oli selvittää, jos oli mahdollista saada yksi ABB:n tuotantolinjoista toimimaan tehokkaammin, kalibrointiprosessia muokkaamalla tietyssä tuotantolinjassa.

Tämän tietyn robotin tarkoitus on noukkia osat kytkimelle. Robotti noukkii osat pahvilaatikosta jossa on useita kytkimen runkoja.

Joskus kun robotti yrittää noukkia osat laatikosta se ei osu oikeaan kohtaan. Tämä johtaa siihen, että tuotantolinja keskeytetään.

Robotti käyttää kameraa nähdäksensä missä kytkimen rungot ovat, ja kamera ottaa joka kerta kuvan, kun yksi runko on noukittu laatikosta. Tällä tavalla robotti tietää ja näkee minkä rungon on noukinut ja mikä on jäljellä laatikossa.

Tekemällä robotin käyttämän kameran kalibrointiprosessi tehokkaammaksi ja sujuvammaksi, voidaan vähentää tuotannon keskeytyksiä. Kalibrointiprosessia analysoitaessa testattiin vaihtoehtoinen ratkaisu, joka vaikuttaisi sopivammalta, sillä se säästää merkittävästi aikaa kalibrointia tehtäessä. Tämä prosessi myös helpottaa tuotantolinjaa valvovan henkilön työtä, sillä kameran kalibrointi on nyt helpompi suorittaa tarvittaessa.

Kieli: Englanti

Avainsanat: konenäkö, optimointi, kalibrointi, automaatio

BACHELOR'S THESIS

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Title: Optimisation of Robot Picking Using Machine Vision

Date: 6.11.2024 Number of pages 38

Abstract

This thesis was done for ABB Smart Power in Vaasa, Finland. ABB manufactures different types of load switches, switch fuses, and changeover switches. The switches are mostly used for solar power, backup power, and industrial power supply backup systems.

The purpose of this thesis was to find an alternative calibration process for a robot's camera, at a specific production line. This specific robot's purpose is to pick up frames for the switches.

The robot picks them up from a cardboard box where there are many frames. Sometimes the robot does not manage to find the frames, which leads to interruptions in the production.

The robot uses a camera to see where the frames are and takes a picture with a camera every time a frame has been picked up from the box. This way the robot knows which frames are left in the box.

By making the calibration process for the camera more efficient it can be possible to get fewer interruptions.

By analysing the calibration process for the robot's camera, it was possible to come up with an alternative process that proved to be just as accurate as the current one and it will save time and be easier for the operator that is supervising the production line to do a camera calibration.

Language: English

Key words: Machine Learning, Optimisation, Calibration, Automation

Table of Contents

1	Introduction.....	1
1.1	Aims of the Study.....	1
1.2	ABB as a company.....	1
1.3	Financials for ABB	2
2	Pre-study.....	3
2.1	Current calibration of the robot's camera.....	5
2.2	Purpose	7
3	Theory.....	8
3.1	Robotstudio.....	8
3.2	Machine Vision.....	8
3.3	Cognex.....	10
3.3.1	Cognex camera, In-Sight 7000.....	10
3.4	In-Sight Vision	10
3.5	Camera calibration.....	11
3.6	Intrinsic parameters.....	11
3.7	Extrinsic parameters	12
3.8	Lens distortion	12
3.9	Calibration process	13
3.10	Checkerboard grid, feature points	15
3.11	Cognex Checkerboard	15
3.12	Data matrix code	16
3.13	Cognex camera parameters	18
3.13.1	Raw2D	19
3.13.2	Camera2D	20
3.13.3	Plate2D.....	21
3.13.4	Stage2D	23
3.13.5	Home2D	24
4	Method	25
5	Results.....	26
5.1	Manual calibration method of the camera.....	26
5.2	Implementation in the production line	31
5.3	Personal reflections	35
6	Discussion and conclusion	36
7	References.....	37

List of Figures

Figure 1. Production line for pole automation.....	3
Figure 2. Image of how the poles are picked up with the robot.....	4
Figure 3. Feature points, how accurate the calibration is.....	6
Figure 4. Machine vision system visually presented. (ResearchGate, Machine vision, 2021)	9
Figure 5. Lens focal length depending on the distance to the object.....	12
Figure 6. Lens distortion visually. (Mathworks, Camera calibration, 2024).....	12
Figure 7. Displaying how the poles are placed in the box.....	14
Figure 8. Checkerboard. Figure 9. Checkerboard with defined origin.....	16
Figure 10. DataMatrix calibration plate with matrix points.....	17
Figure 11. Cognex camera parameters (Cognex, Calibration Introduction, 2021).....	18
Figure 12. Pixel coordinate system, Raw2D space. (Cognex, Raw2D, 2021).....	19
Figure 13. How the object is visible from the camera angle. (Cognex, Camera2D, 2021)..	20
Figure 14. Calibration Plate Coordinate system. (Cognex, Plate2D, 2021).....	21
Figure 15. Plate 2D with matrix points using a 2mm grid pitch. (Cognex, Plate2D, 2021) .	22
Figure 16. Coordinate system attached to the center. (Cognex, Stage2D, 2021).....	23
Figure 17. Reference space for all coordinate points. (Cognex, Home2D, 2021).....	24
Figure 18. Manual camera calibration setup using first an A4 paper with a checkerboard, then an A4 paper with a black square with the measurements of 50 mm * 50 mm.	27
Figure 19. Data from black square calibration.	28
Figure 20. How accurately does the robot see the 50 mm * 50 mm square, on different layers, at the height-adjustable desk.	29
Figure 21. The number of pixels seen in the square.	30
Figure 22. Calibration data from the production line.	31
Figure 23. Poles in the cardboard box, the second layer of poles is visible. The white A4 paper with the black square gets moved around the corners and midpoint.	32
Figure 24. How accurately the robot sees the measurements of the 50 mm * 50 mm square, on different layers, at the production line.	33
Figure 25. The number of pixels seen in the square, at the production line.	34

Abbreviations

Pole	The shell for the switch.
FOV	Field Of View means how wide of an angle can be seen from a camera lens. Usually measured in degrees (°).
QR-code	Quick response code, a two-dimensional code that stores information. Can for instance be read by a scanner or smartphone's camera.
PLC	Programmable Logic Controller, usually a specialized computer for industrial processes used to control machines.
HMI	Human Machine Interface, A device that lets humans interact and control robots. Used for making quick adjustments.
Distortion	When straight lines of an image appear to be curved unnaturally or deformed.
LED	Light-Emitting Diode.

1 Introduction

In industrial production, there are always improvements to be made. It can be time savings, cost savings, improved automation, data integration, or overall more energy-efficient production. In this thesis, I am going to analyse and try to find a more efficient way to operate a specific production line. The main goal is to improve the automation of processes that can lead to less human attention.

1.1 Aims of the Study

The main purpose of this thesis is to find out if a specific production line can be more efficient and remove possible errors that result in delays and more human attention. The focus is on a robot in the production line assembling poles used for switches at ABB Smart Power.

1.2 ABB as a company

ABB (Asea Brown Boveri) is a market leader when it comes to electrification and automation. Today, the corporation employs over 105 000 employees in over 100 countries. ABB's roots go back to 1883 when ASEA was founded in Sweden. They started manufacturing electrical lights and generators. Eight years later, in 1891, the Swiss company Brown, Boveri, and Cie was founded, producing AC and DC motors, transformers, generators, and steam turbines.

Around a century later, in 1987, the two companies merged into what is now known as ABB. ABB currently has two headquarters, in Västerås, Sweden, and Zurich, Switzerland. In Finland, ABB employs over 5 000 people and operates in over 20 cities. Currently, it is one of the most popular employers in the technology industry in Finland.

ABB Smart Power is a manufacturing unit within ABB that is industry-leading when it comes to the manufacturing of load switches, switch fuses, and changeover switches.

The switches are mostly used for solar power, backup power, and industrial power supply backup systems. (ABB, History, 2024)

1.3 Financials for ABB

ABB had a great financial year in 2023. The company had an order intake of \$33.818 billion, and its revenue was \$32.235 billion. Gross profit was \$11.214 billion, or 34,8% of their revenue. The order intake stayed the same as in 2022, but revenue and gross profit increased by 9% and 15%, respectively. The biggest financial gain was their improved operational EBITDA and very strong cash flow year on year. Operational EBITDA increased by 16,9 % to \$5.427 billion, and cash flow from operating activities increased by 233% to \$4.290 billion in the financial year 2023. They paid a dividend of CHF 0.87 per share. (ABB, Q4-2023 press release, 2024)

2 Pre-study

In the production line in focus, one of ABB's many poles is manufactured. The manufacturing process includes the whole production process and assembly and adding all the components together to get the final product. The production line consists of many elements, and there are several robots in the production line that all have different tasks. The 3D picture below represents what the production line looks like with the robots and their working stations.

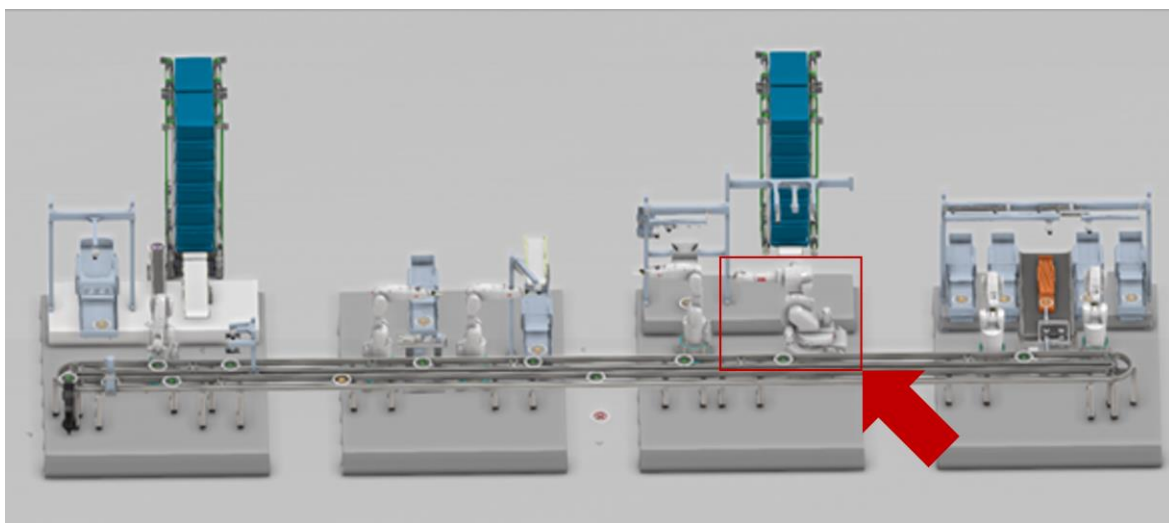


Figure 1. Production line for pole automation.

The part of the production process that is in focus is the second station from right out of the four, marked as the red square, where a robot picks up preassembled shells for the poles from a box, adds a window piece, and then places the shells on a conveyor belt, where they will later get their manufacturing QR code and some more features.

It takes the parts from a cardboard box containing over a hundred pole frames in total. The robot uses a camera that takes a picture every time a frame is picked up, so it knows what frames are left and where they are placed in the box. When taking the picture, the robot finds where the frames are based on a coordinate system that is integrated into the camera's software. After taking the picture, the camera sometimes gets manually calibrated when needed, so it will be as accurate as possible when picking up the next frame. The most crucial part is that the robot finds the correct coordinates for the frames

for the poles it will pick up; otherwise, it can cause the robot to damage the frames for the poles or not be able to find them. This will lead to interruptions on the production line.



Figure 2. Image of how the frames are picked up with the robot.

2.1 Current calibration of the robot's camera

A standard calibration was done to see how the process works now. To be able to do this, the production line had to be interrupted.

During the process, each frame for the pole had to be manually placed on the starting point where the robot picked them up. This had to be done for each frame, a total of 24 times. The robot picked up the frames one by one and placed them in the corners of an empty rectangular cardboard box to get calibration points for the location of the switch. A total of six frames were placed in the box for the first layer. One in each corner and one in the middle between the corners on the wider side of the box.

After the six frames were placed in the box, a calibration was made to get the coordinates of the frames to determine whether they correspond to their correct coordinates. When this was done, a picture of the box layout was taken to be able to proceed with the next layer of frames.

The robot proceeded to do the same thing again and placed six new frames on top of the first layer. This required manual adjustments by hand when a frame was not exactly on top of the first one. When the frames were appropriately placed, a new calibration was done. This made it possible to check that the calibration matched the coordinates and that they met the criteria. The criteria are that the frames are precisely on top of each other and that the coordinates from the current and previous layers are strictly on the same x and y coordinates. Otherwise, when the third and fourth layers of frames are placed, the coordinates might not be aligned with the other layers.

The robot continued to stack a third and fourth layer of frames. Some manual adjustments to the frames had to be made when the robot sometimes failed to place a frame directly on top of the frame underneath.

When all four layers were done, all the calibration points were saved for 24 frames. This would then be transferred to robotic software so that the robot would be able to use the results in the future. This gave an understanding of how well the robot managed to perform its tasks, and how much the coordinates differentiated on the fourth layer compared to the first.

This calibration was accurate but very time-consuming. It took around 90 minutes to perform. The total number of feature points is one way to measure the accuracy of the calibration. In Figure 3, the result shows the total number of feature points that were extracted and used in the calibration. Average error displays the average error in pixels, and maximum error displays the maximum error in pixels. The result from the calibration can be shown in the figure below. There is also a feature points table that displays all the coordinates extracted from the image. The results give a graphical indication of how good the calibration was. If the average error is less than 0,25 it is an excellent result. The average error for the test results is 0,087 pixels.

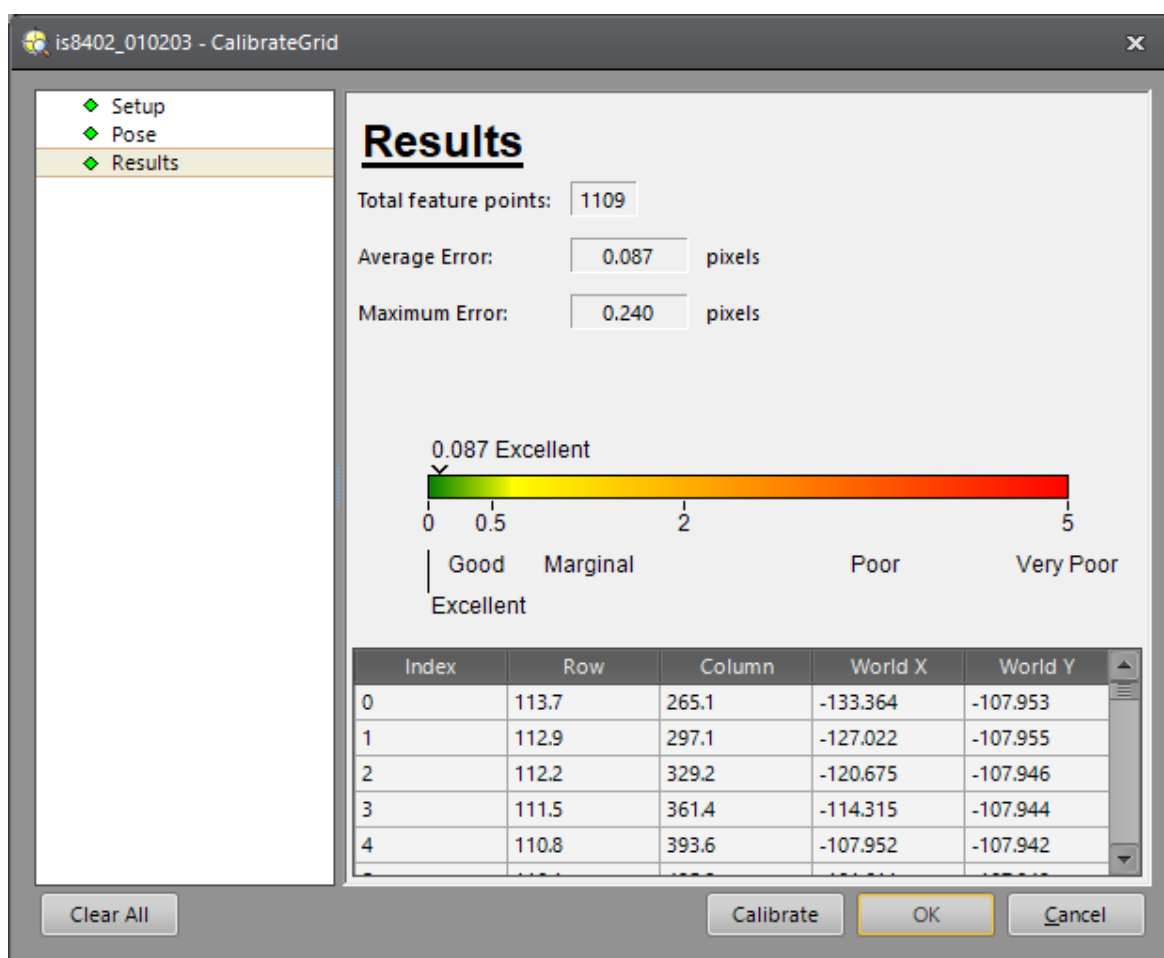


Figure 3. Feature points, how accurate the calibration is.

2.2 Purpose

The main purpose of this study is to improve the calibration process of the robot to lower interruption times and improve overall production efficiency. The focus is on the calibration process for the robot's camera and how to get even more accurate calibration results.

3 Theory

Many key components are taken into consideration when making camera calibrations. Each section is important and will be explained below.

3.1 Robotstudio

Robotstudio is an advanced simulation and programming tool made by ABB used for robotic applications. It is the world's most used offline programming tool for robotics.

It is software used for ABB robots on how they operate. The software lets you build, test, and refine your robot installation in a virtual environment. It lets you program the robot, configure the robot, and optimize production lines. It is also possible to implement the use of virtual and augmented reality in programming and simulation. (ABB, Robotstudio, 2024)

The program allows you to perform simulations and programming without disturbing the ongoing production process.

3.2 Machine Vision

Machine vision is a technology used for robot guidance and automatic inspections of objects. Both hardware and software are utilized to help guide operations, relying on the images captured by the system. Machine vision allows industrial equipment to see and detect features or flaws, providing operational guidance to devices. It can then see objects, analyse what it sees, and then act based on the analysis. The system can use the images to make fast decisions based on what it sees within visual inspection, process control, and material inspection. (Zebra Technologies, What is machine vision, 2024)

A machine vision system has four key components it uses. When combining them, it is possible to get accurate measurements and results. The first one is a light source that is used to illuminate objects. Optimal light makes it possible to get more accurate and detailed results since it allows the features to stand out from the inspected element.

The second key component is the camera, which provides a sensor and lens to be able to capture and digitalize the image in the camera's field of view (FOV). A special camera is used that is designed to process and understand images similarly to how humans see them. The camera can recognize patterns and identify objects. It can also detect deviations.

The third and fourth components includes using a computer to be able to process and handle the images that the camera captures. The computer analyzes the images and then uses hardware and communication links, such as a PLC, HMI, or robot.

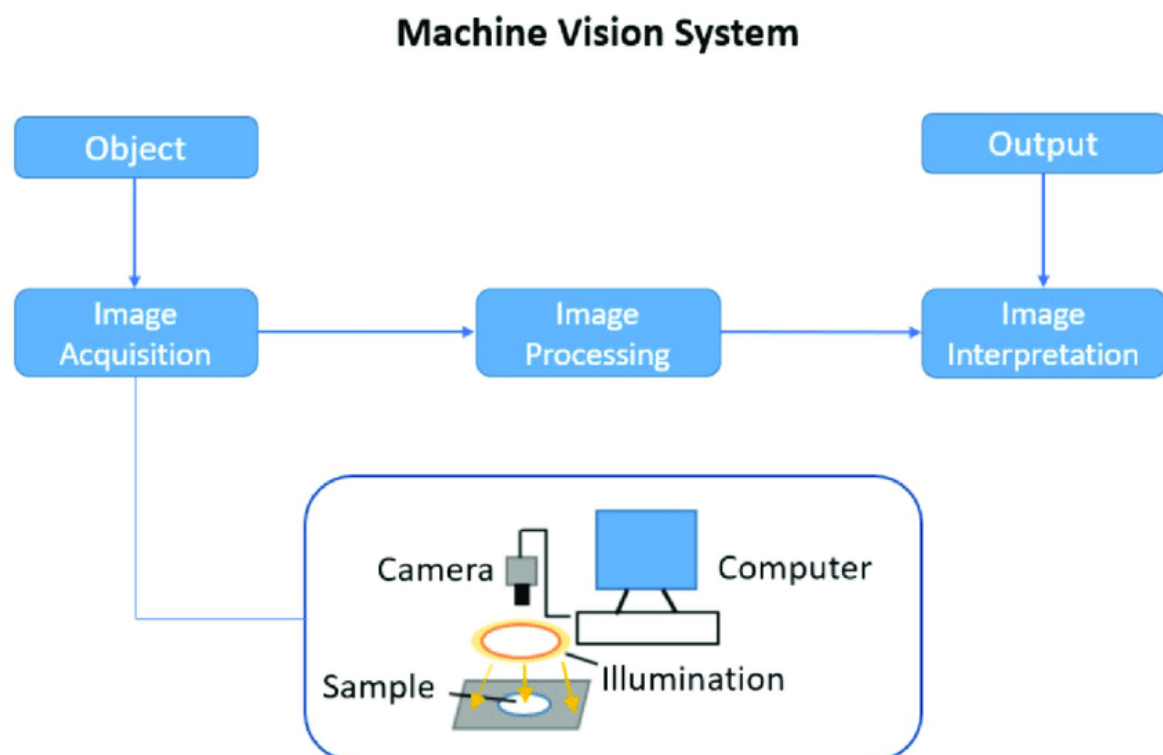


Figure 4. Machine vision system visually presented. (ResearchGate, Machine vision, 2021)

3.3 Cognex

Cognex is the manufacturer of the camera that is being used by the robot to see all the components it must pick up, move, or assemble. The company is the world's leading provider of vision systems, sensors, software, and industrial barcode readers used for automation in manufacturing. (Cognex, In-Sight, 2024)

3.3.1 Cognex camera, In-Sight 7000

There are many different camera vision systems that Cognex provides, and the model used for this robot is the Cognex In-Sight 7000 Vision System. It is a powerful vision system with a full range of features that performs fast and accurate inspections. The camera system is thoughtfully engineered with convenient features to solve industrial applications. It is ideal for inspecting automated manufacturing operations in an industrial environment. (Cognex, In-Sight 7000, 2024)

3.4 In-Sight Vision

The camera uses its integrated In-Sight Machine Vision System, and it is programmed to perform visual inspections of an object. The tasks of the system are to know what to look for in the image, such as details, shadows, and patterns. It is also important to know how to get the best illumination possible for the object. For this, optimal lighting is required.

When taking an image, the camera lens captures light energy from the area seen by the in-sight vision system and then converts it into a digital format. It uses a 2D grid of values called pixels. Each pixel corresponds to a location in the (X, Y) coordinate system.

In-Sight Vision can be integrated into Robotstudio. This will then seamlessly communicate with both the robot and the camera. This makes it possible to mainly use Robotstudio for calibrations and readings without having to use a different program when calibrating the camera and making adjustments. This saves the programmer substantial time and minimizes the risk of errors.

3.5 Camera calibration

Camera calibration is a process to calculate specific parameters to get certain measurements. With camera calibration, the most important tasks are to get measurements of an object and apply corrections for lens distortion.

3.6 Intrinsic parameters

The intrinsic parameters represent parameters for the camera itself and how it captures the image. The most important factor is focal length, which tells us the angle of view. This tells us how much of a scene or object will be captured and how large the elements captured are, depending on the distance between the image plane and the center of projection. Other parameters include scale factor, skew factor, aperture, and resolution.

The scale factor refers to the numerical value that is used to multiply all the elements of an object in order.

The skew factor measures the asymmetry of a distribution. If the x and y axes are not perpendicular to the original angle of the object, there will be a skew. The skewness value can be positive, zero, negative, or undefined. When there is no skew, it has the value of 1.

Aperture is how much the camera lens is open. It can change the amount of light passing through the lens. When taking an image of a dark object, the lens is wide open, and when taking an image of a bright object, the lens is less open due to less light needed to illuminate the object in focus.

Resolution is how detailed a picture will be. Higher resolution means more details. It is usually measured in dots per inch (DPI). (Towards Data Science, Extrinsic camera parameters in computer vision, 2022)

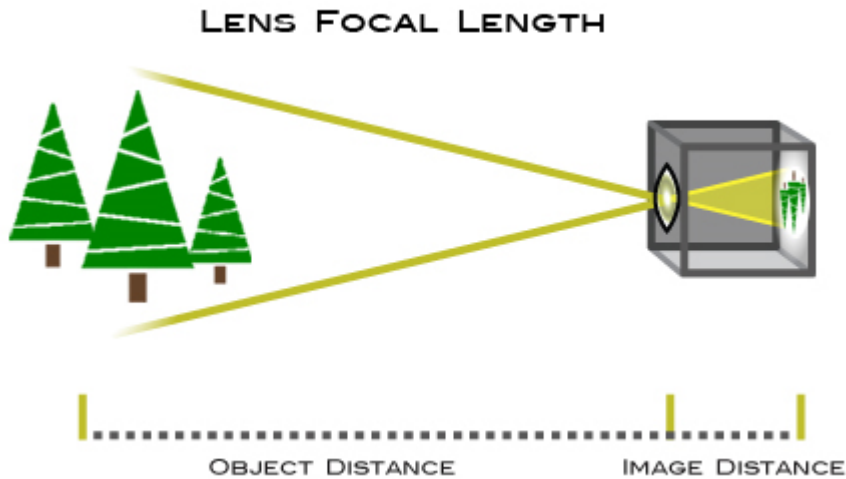


Figure 5. Lens focal length depending on the distance to the object.
(Nikon Corporation, Focal length, 2012)

3.7 Extrinsic parameters

Extrinsic parameters are the relationship between the coordinate system of the camera and the object in focus. The extrinsic parameters of the camera depend on its orientation and location. (Sciencedirect, Extrinsic parameter, 2019)

3.8 Lens distortion

Lens distortion is something you want to minimize. This is when light rays bend more near the edges of a lens compared to the center. How much distortion there is depends on what kind of lens is used for the image that is captured. There are wide-angle lenses, zoom lenses, and telephoto lenses. Here are three examples of how distortion can manipulate an image.

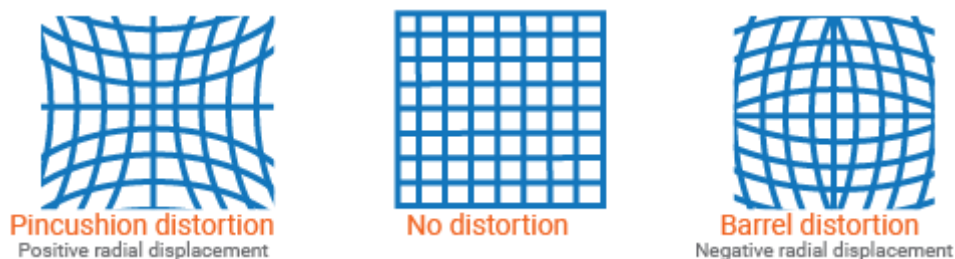


Figure 6. Lens distortion visually. (Mathworks, Camera calibration, 2024)

Barrel distortion and pincushion distortion are the two most common types of lens distortion. Barrel distortion is commonly seen with wide-angle lenses when the field of view (FOV) is much wider than the size of the image sensor and with zoom lenses with comparatively short focal lengths. This means that the image needs to be squeezed to fit into the frame. Near the edges of the image, this can be noticed the most. The lines are not straight and visibly curving inward. (Mathworks, Camera calibration, 2024)

Pincushion distortion is the opposite of barrel distortion. Lines are curved outward from the center of the image. This is the result when the FOV is smaller than the size of the image sensor, making the image stretch to fit in the frame. This commonly happens with telephoto lenses due to image magnification increasing towards the edges of the frame in relation to the optical axis. (Mathworks, Camera calibration, 2024)

The distortion can also be calculated using the radial distortion formula. (Mathworks, Camera calibration, 2024)

$$x_{distorted} = x(1 + k_1 * r^2 + k_2 * r^4 + k_3 * r^6)$$

$$y_{distorted} = y(1 + k_1 * r^2 + k_2 * r^4 + k_3 * r^6)$$

The x and y are the undistorted locations of the pixels. They are calculated from pixel coordinates by translating the optical point and dividing by the focal length in pixels.

k_1, k_2, k_3 are the radial distortion coefficients.

$$r_2 = x^2 + y^2.$$

3.9 Calibration process

This section gives a more in-depth explanation of the parameters for the calibration process of the camera. The frames are prefilled in a cardboard box that fits up to 29 pieces per layer. The box can hold up to four layers of poles, bringing the total number of frames to 116. When the frames come to the production line, they come in a prefilled box. The robot must pick them up one by one. For the current calibration process, an empty box is being used that is manually filled with poles, and a picture gets taken every time a pole gets picked up by the robot from the box.

An LED bar is the type of light used for the camera so that the robot sees the frames and the details of the frames become the most visible. The LED bar is strategically positioned to provide optimal illumination to the target area from a precise angle. The angle is adjusted so that there are as few shadows as possible. An LED bar is good to use in this process because it can add contrast and highlight features of the objects in focus. In the picture below, it is possible to see how the light from the LED bar is reflected on the surface of the frames. Since the camera is placed at the center of the coordinate system, it can eliminate most of the shadows. There are still some shadows, especially on the frames near the corners where the angle from the camera to the poles is greater than in the middle of the box. This is only seen when zooming in closely on the picture.

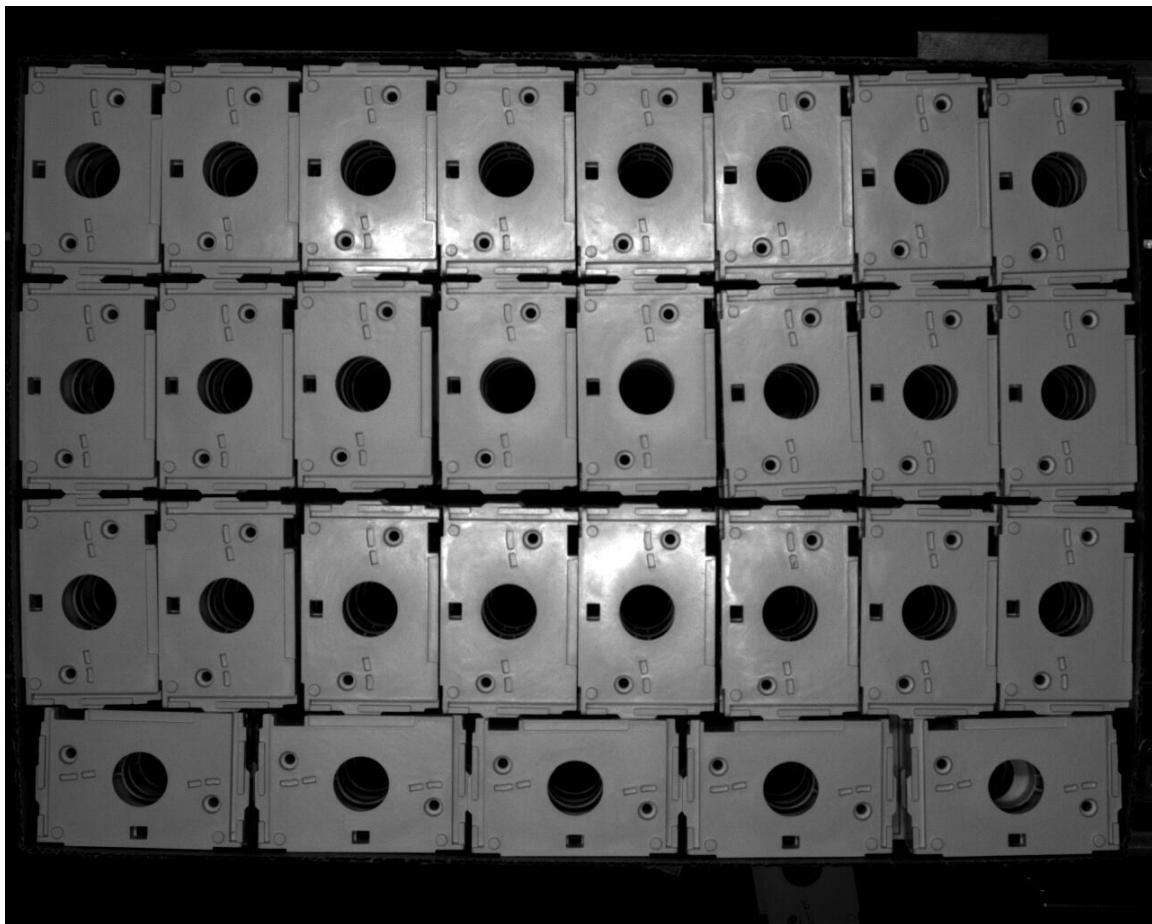


Figure 7. Displaying how the frames for the poles are placed in the box.

There is a little bit of barrel distortion, especially near the edges. It is the most visible when zooming in on the top left frame. The reason for this is that the camera's field of view is

broader than the image sensor. This can sometimes cause problems for the robot to pick up the switches since the coordinates of the frames can be harder to find.

3.10 Checkerboard grid, feature points

A calibration checkerboard grid pattern is used for the coordinates. It has a specific size and spacing for the cells that make up the pattern. When the picture is taken, the calibration software will identify as many feature points as possible. Feature points are characteristics that define a part. The corners of a part, the edges of a part, and the fiducials of a part are the three main components for identifying feature points in the pattern. The fiducial works as a locator or registration point. When the calibration is performed, the software will begin to compute the calibration and report a "Calibration Score" based on the spacing of feature points. Afterward, the calibration result gets stored and can be used for the same tasks the robot will perform in the future on the same work object.

3.11 Cognex Checkerboard

For the camera calibration, a checkerboard is being used. It uses black and white tiles; all tiles are squares with the same height and width.

It is important that the checkerboard is within the field of view (FOV) of the camera and that the camera is placed at an optimal angle to minimize lens and perspective distortion.

For the calibration, Cognex's software is being used. A standard calibration plate with specific measurements for the tiles or squares is utilized. The size of the squares can differ from 0,5mm, 1mm, 2mm, 5mm, and 10mm.

The tiles provide references for the vision of how real equal-distance points are distributed under the camera, thus helping to calculate how many lens or perspective distortions the camera has. (Cognex, Checkerboard calibration, 2021)

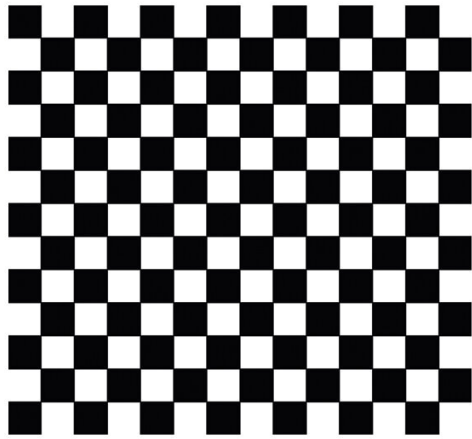


Figure 8. Checkerboard.

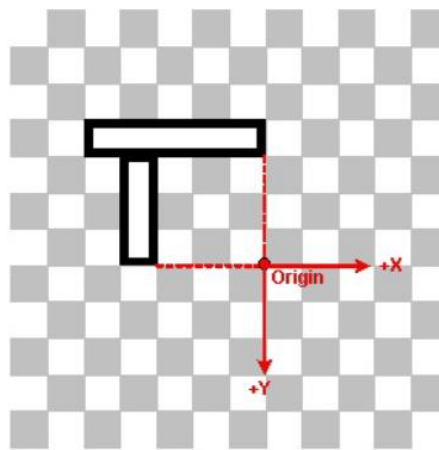


Figure 9. Checkerboard with defined origin.

For the calibration, a combination of the above two checkerboards is used. The left one does not have standard references for the x and y directions, meaning the origin, x, and y axes must be manually selected. The size or pitch of the squares that are most optimal for calibration is 5 millimeters in length and width.

With the right one, the robot's center coordinate (origin) can be automatically defined. The pattern in the right image helps the camera locate the object and determine the orientation of the code. When combining both checkerboards, the robot's center coordinate can be "transformed" to the other checkerboard, so it understands the coordinates for the object.

3.12 Data matrix code

A data matrix is a code in two dimensions consisting of black and white cells. It can encode huge amounts of data in a small amount of space. Up to 2335 alphanumeric and 3116 numerical characters can be encoded. The size of the code modules varies from 10 x 10 modules up to 144 x 144 modules. The code is either arranged in a square or rectangular arrangement. The code can be read in both directions; the camera lens sees the coordinates of the cells and can transfer the data to the robot. (Keyence, Data matrix, 2024)

Cognex uses the newest version of Data Matrix, ECC 200. This version uses the Reed-Solomon algorithm for error and erasure recovery. The ECC 200 version enables codes that

have been up to 30% damaged to be restored. The error rate is less than 1 in 10 million characters scanned. (Cognex, Data matrix codes, 2024)

The DataMatrix calibration plate uses codes to mark the locations of multiple grid vertexes (points where the line contacts another coordinate point). Figure number 9 shows four vertexes marked on the checkerboard calibration plate. These contain data that translates to their location on the checkerboard. (Cognex, Data matrix codes, 2024)

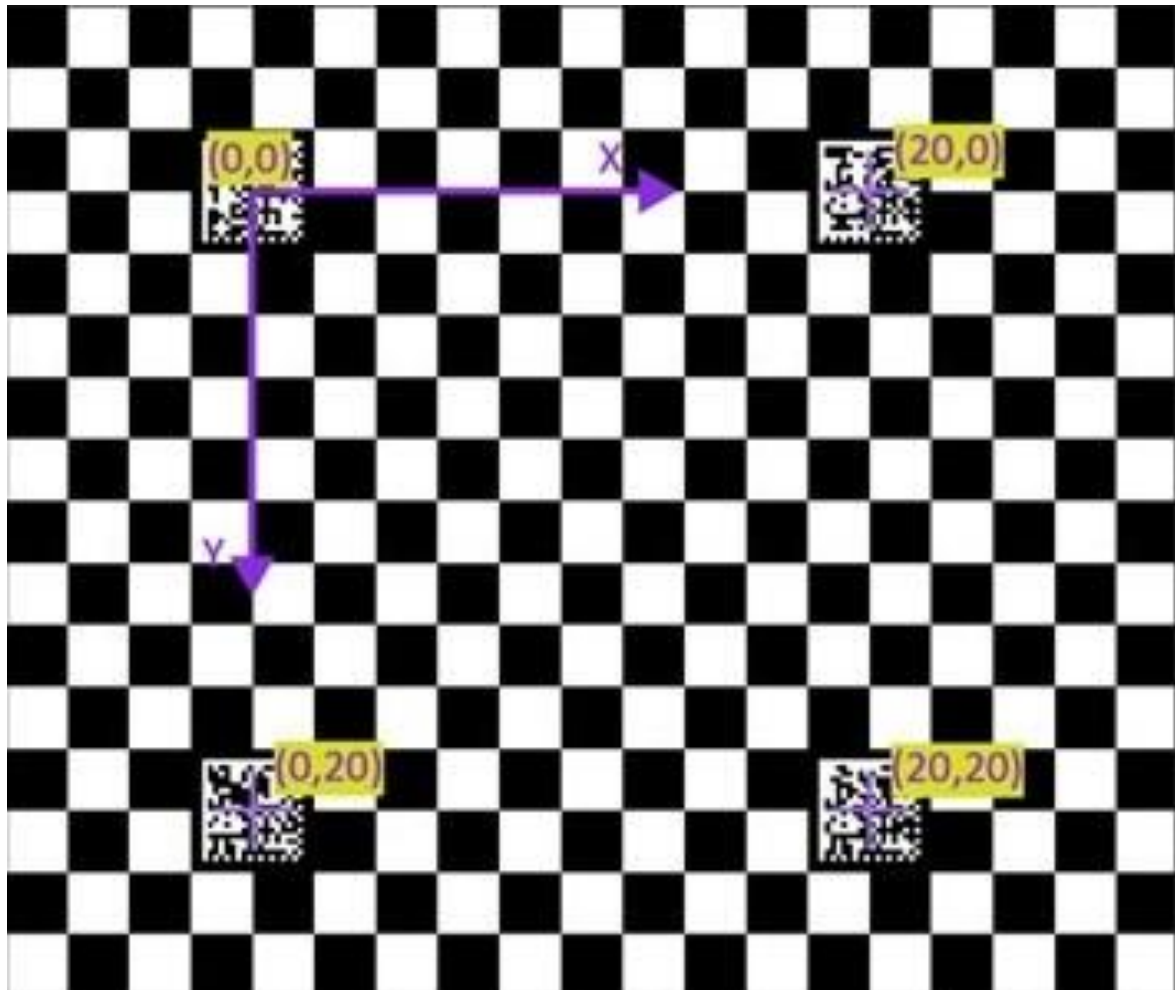


Figure 10. DataMatrix calibration plate with matrix points

3.13 Cognex camera parameters

There are several parameters for the robots and camera coordinates mapped in a shared system; all feature locations get transformed into Home2D coordinates. Home2D is the base reference space where all coordinates and their relations are described. When the coordinates are described in Home2D, they will be used to calculate how the robot should operate. By doing this, it is possible to get the most accurate measurements. There are a total of five spaces that are used for both run-time feature finding and calibration. These are: Raw2D, Camera2D, Plate2D, Stage2D, and Home2D. In the below picture, all stages are combined. (Cognex, Calibration introduction, 2021)

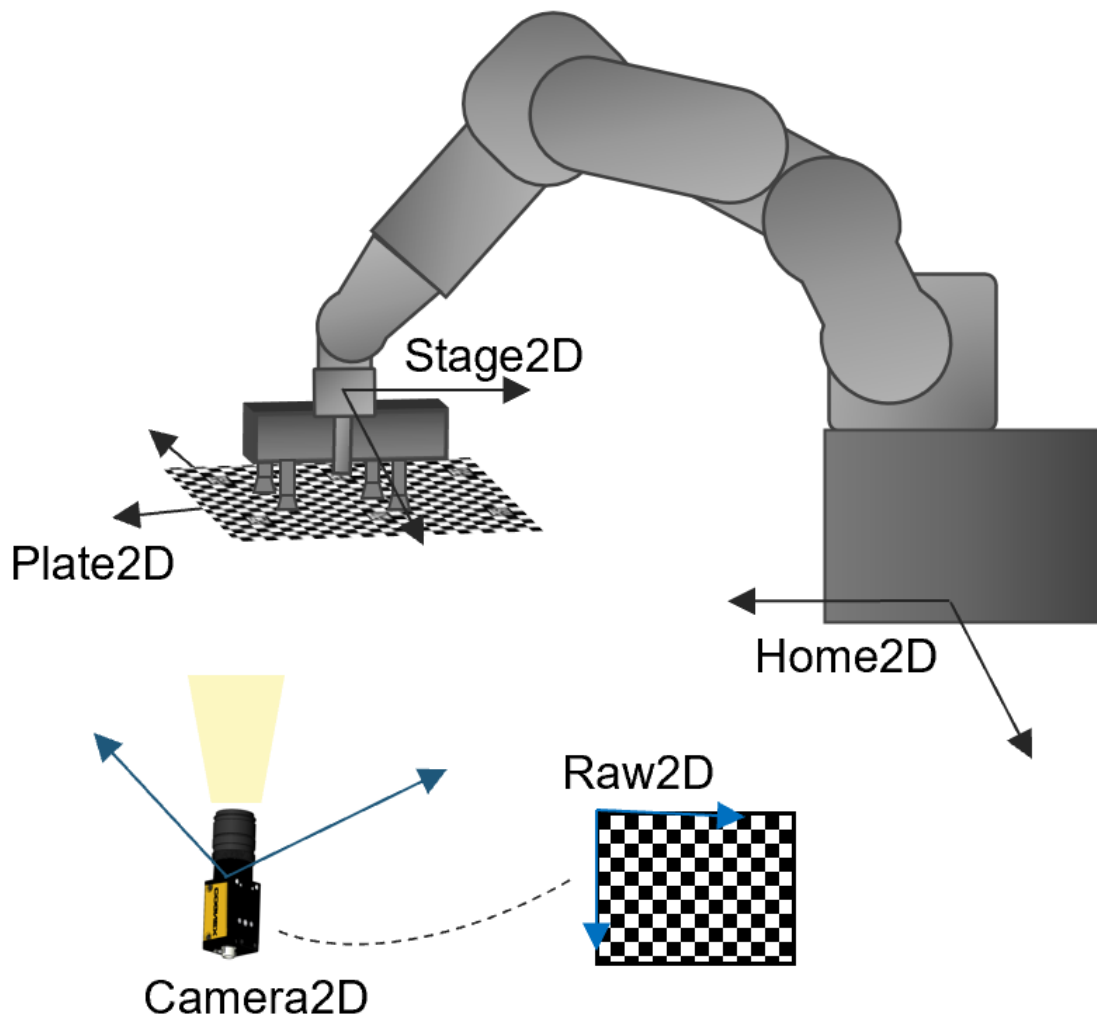


Figure 11. Cognex camera parameters (Cognex, Calibration Introduction, 2021)

3.13.1 Raw2D

This is the pixel-space coordinate system of the camera. It measures how far the object in focus is from the origin on the x and y axes. In the below picture, the smartphone's placement will get coordinates against the origin of the x, y coordinate system.

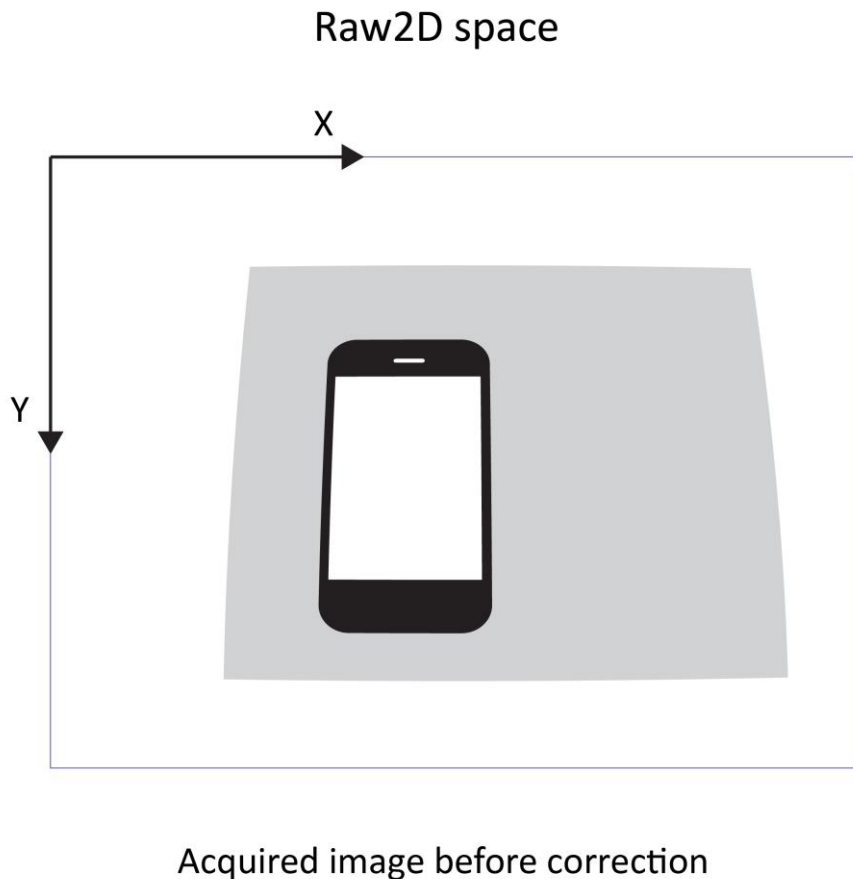


Figure 12. Pixel coordinate system, Raw2D space. (Cognex, Raw2D, 2021)

3.13.2 Camera2D

The camera utilizes the physical orthonormal coordinate system. The origin of Camera2D is at the center of the camera's image window. The X axis is parallel to the direction of the Raw2D X axis. The Camera2D's Y axis is perpendicular to the direction of the X axis and points in the general direction of the Raw2D Y axis.

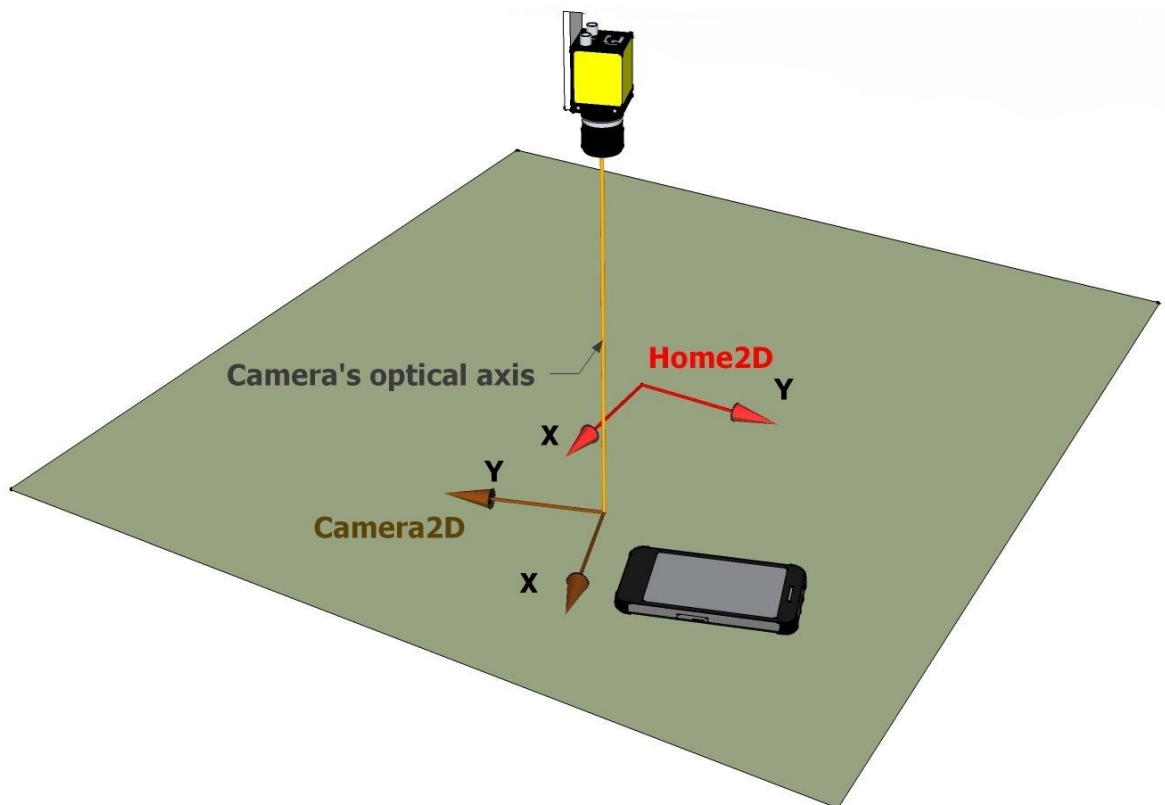


Figure 13. How the object is visible from the camera angle. (Cognex, Camera2D, 2021)

3.13.3 Plate2D

This is the coordinate system that is being used for the calibration plate. All the calibration features are described in the same Plate2D coordinate system. In the Plate2D coordinate checkerboard there are data matrix codes that mark positions for calibration points.

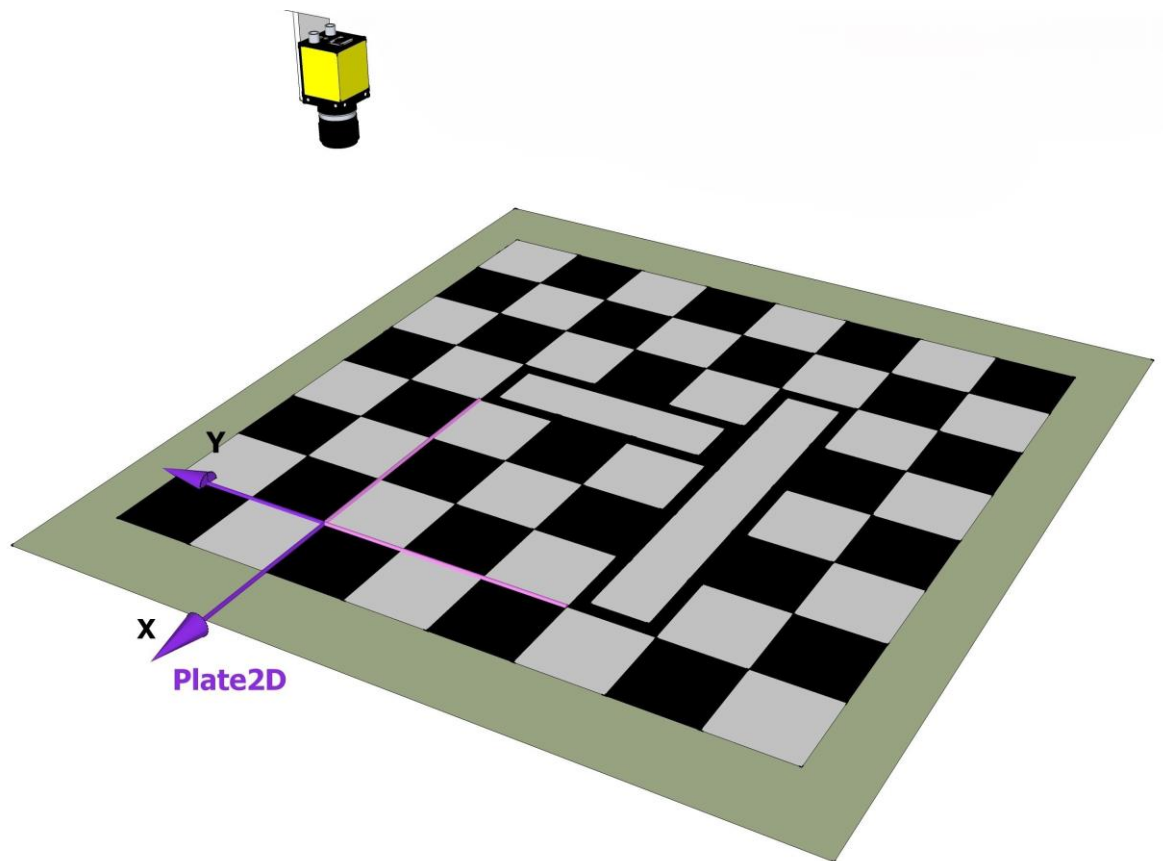


Figure 14. Calibration Plate Coordinate system. (Cognex, Plate2D, 2021)

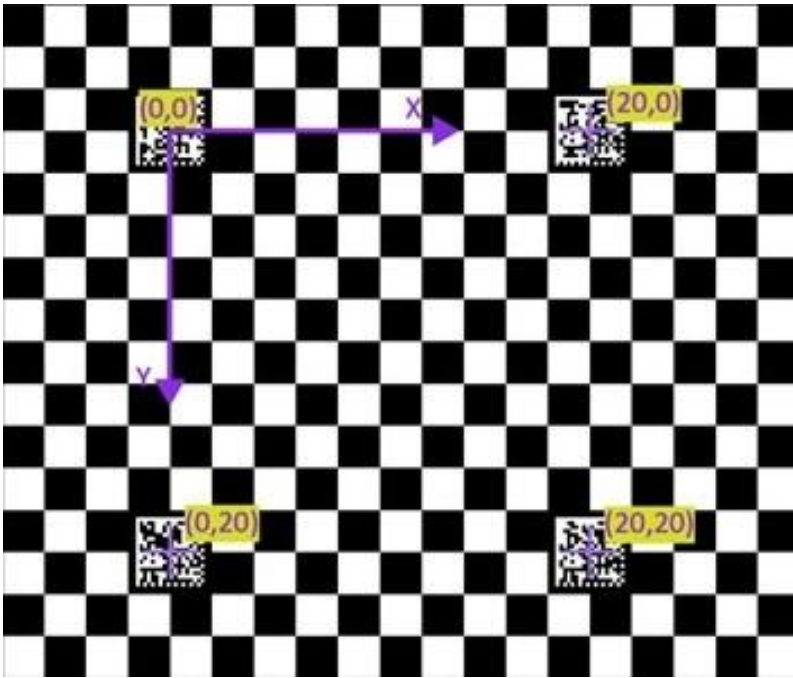


Figure 15. Plate 2D with matrix points using a 2mm grid pitch. (Cognex, Plate2D, 2021)

3.13.4 Stage2D

Stage2D is an orthonormal coordinate system attached to the motion stage's center of rotation. It moves and rotates along with the motion stage. Stage2D matches the Home2D in the initial position of the stage.

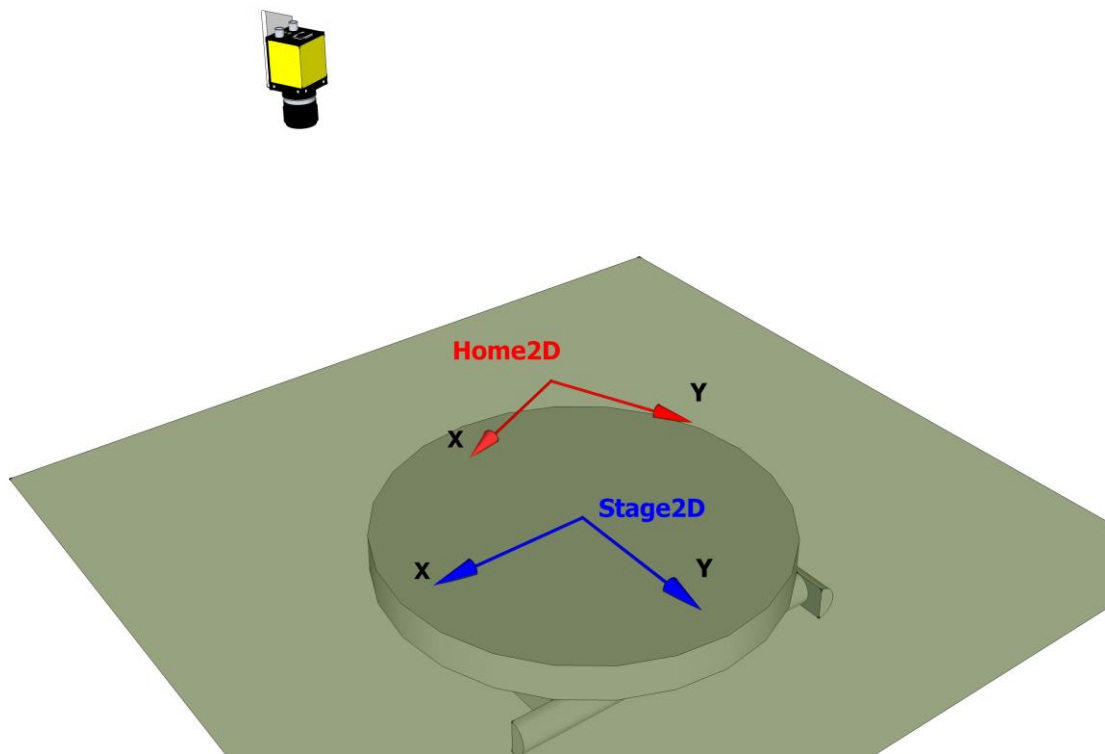


Figure 16. Coordinate system attached to the center. (Cognex, Stage2D, 2021)

3.13.5 Home2D

This is the reference space where all coordinate points are, and how they relate to each other is being described. Home2D is defined by the initial position of the motion stage and has the coordinates where (X, Y, and Theta) are (0, 0, 0).

Home2D's X-axis is aligned perfectly with the motion stage's X-axis. The Y axis of Home2D is at a 90-degree angle from the X axis and in the general direction of the motion stage's Y axis.

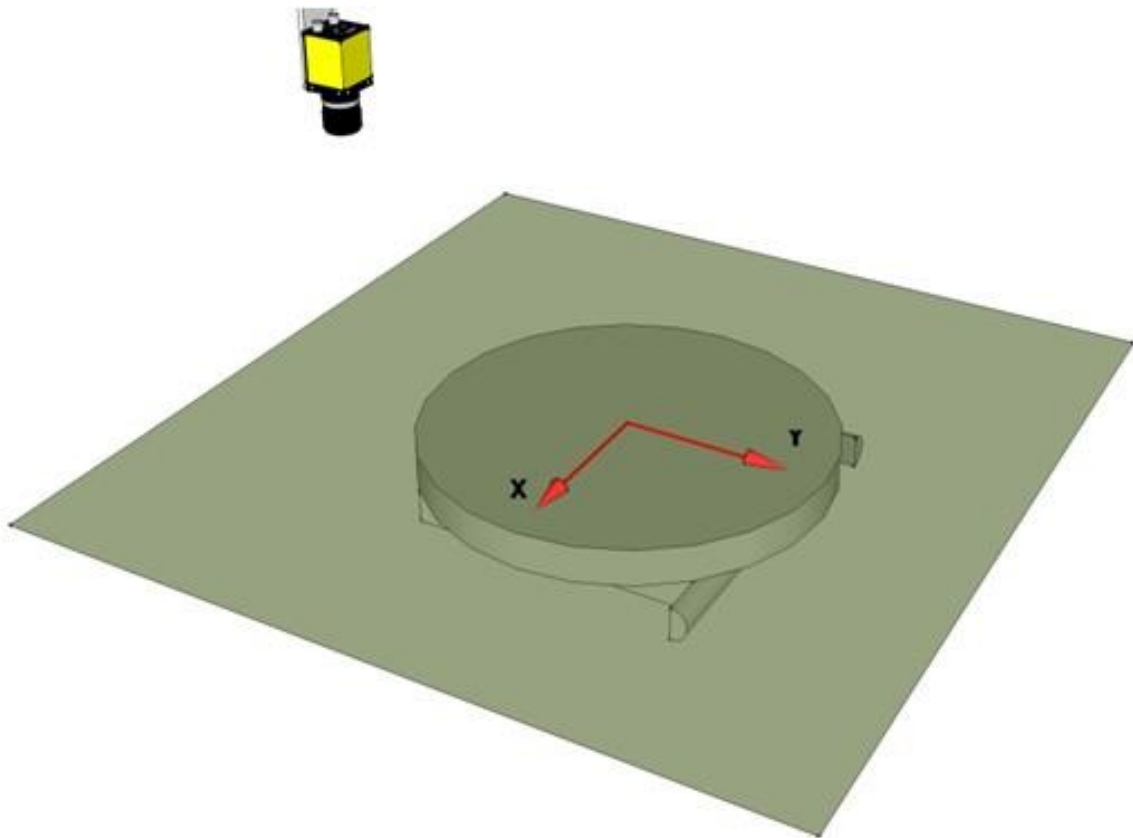


Figure 17. Reference space for all coordinate points. (Cognex, Home2D, 2021)

4 Method

There are several options when choosing a method. To choose the optimal method, the current calibration process of the robot's camera was analysed. This provided the necessary tools and parameters to modify the calibration process.

After discussing my ideas with my supervisor for an alternative calibration process, a method was tested both in simulation and in practice. The method that got implemented involved a manual camera calibration done with different heights, using both a checkerboard grid and an A4 paper. The A4 paper has a black square, that helps the camera to give accurate measurements since the square's measurements are given.

This is tested and explained in the results section. The alternative method will also be compared to the current calibration method.

5 Results

The results of the chosen method are displayed in the different graphs, in Figures 20, 21, 24 and 25.

5.1 Manual calibration method of the camera

To be able to improve or change the camera calibration process, a manual calibration had to be done. For this to work, one method is to calibrate the camera for each layer of frames with different heights, using a calibration grid and manually inserting data into the calibration software.

At the production line, there are four layers of frames. To get the most accurate calibration results, it is best to do four separate calibrations, one for each layer of frames. This was put into practice at the production line as the calibration method.

A Cognex camera got rigged up to a camera mount next to a height-adjustable desk. Then it was possible to connect the camera to a power supply and a laptop to get readings from the camera. The images from the camera were analysed with Robotstudio and In-Sight Vision software.

By adjusting the height of the camera in relation to the height of the white A4 paper with the square and the checkerboard, it was possible to get accurate measurements, for four different levels.

For calibration of the camera, many images were taken. First, a checkerboard grid with fiducials was used to get the right data for the calibration. Then the paper was switched to a white A4 paper with a black square with the measurements of 50 mm* 50 mm. The black square helps the camera to find a specific object and get accurate results since it is easy to see the square and its measurements.

The camera searches in its field of view where the square is, and in the software, the measurement of the square is integrated, so it always knows to look for the square and its measurements. Images with the camera were taken multiple times, and for every

image, the white paper with the square was moved around the camera's field of view to get many results for the test. This gave the Robotstudio software many readings that were used for the calibration.

After fourteen images were taken, a calibration was performed to determine the camera's accuracy in measuring the square's dimensions.



Figure 18. Manual camera calibration setup using first an A4 paper with a checkerboard, then an A4 paper with a black square with the measurements of 50 mm * 50 mm.

	A	B	C	D	E	F	G	H	I	J	K
18											
19		Index	Row	Col	Angle	Scale	Score				
20	Patterns	0.000	560.230	782.753	0.001	100.006	99.997				
21											
22	Pixel										
23		Row0	Col0	Row1	Col1	Score					
24	Edges	492.126	705.256	633.996	711.333	-89.415					
25	Edges	630.207	859.082	488.368	852.308	-82.426					
26											
27		Row0	Col0	Row1	Col1	Angle	Distance				
28	Dist	563.061	708.294	559.288	855.695	91.467	147.449				
29											
30	Millimeter										
31		Row0	Col0	Row1	Col1	Score					
32	Edges	-9.532	69.912	38.288	71.509	-89.415					
33	Edges	37.507	121.280	-10.366	119.469	-82.426					
34											
35		Row0	Col0	Row1	Col1	Angle	Distance				
36	Dist	14.378	70.711	13.570	120.375	90.932	49.671				
37											

The screenshot shows the In-Sight software interface. At the top is a data table with columns A through K and rows 18 through 37. The table contains various parameters for black square calibration, including Index, Row, Col, Angle, Scale, Score, Edges, Dist, and Millimeter. Below the table is a sequence of 12 small images showing a black square being moved around. The interface also includes a 'PC' and 'Sensor' section, a progress bar, and navigation buttons. At the bottom, there is a status bar with 'Col', 'Job: 3.5 ms', '5540 Available Cells', and 'Offline'.

Figure 19. Data from black square calibration.

The In-Sight software is used for this. The last row represents the images taken by the camera when the square is moved around to get many pictures.

The most important parameter is the square's measurements. To get them, the distance between the square's edges is measured. The software knows that the square is 50 mm * 50 mm.

In the last cell, the distance between the edges visible by the camera is displayed. The square is not within the camera's view at precisely 50 mm * 50 mm. The average deviation varies between 49,44 mm and 49,84 mm, giving an accuracy of 0,6 mm from the desired measurement of 50 mm. An appropriate camera and lens are chosen based on the precision level of 0,6 millimeters.

After calibrating the first layer, the electrical desk was raised by 35 millimeters to align closely with the height of the second layer of poles within the cardboard box on the production line. The same process was also performed for the third and fourth layers, by raising the table again and taking images with the camera of the square.

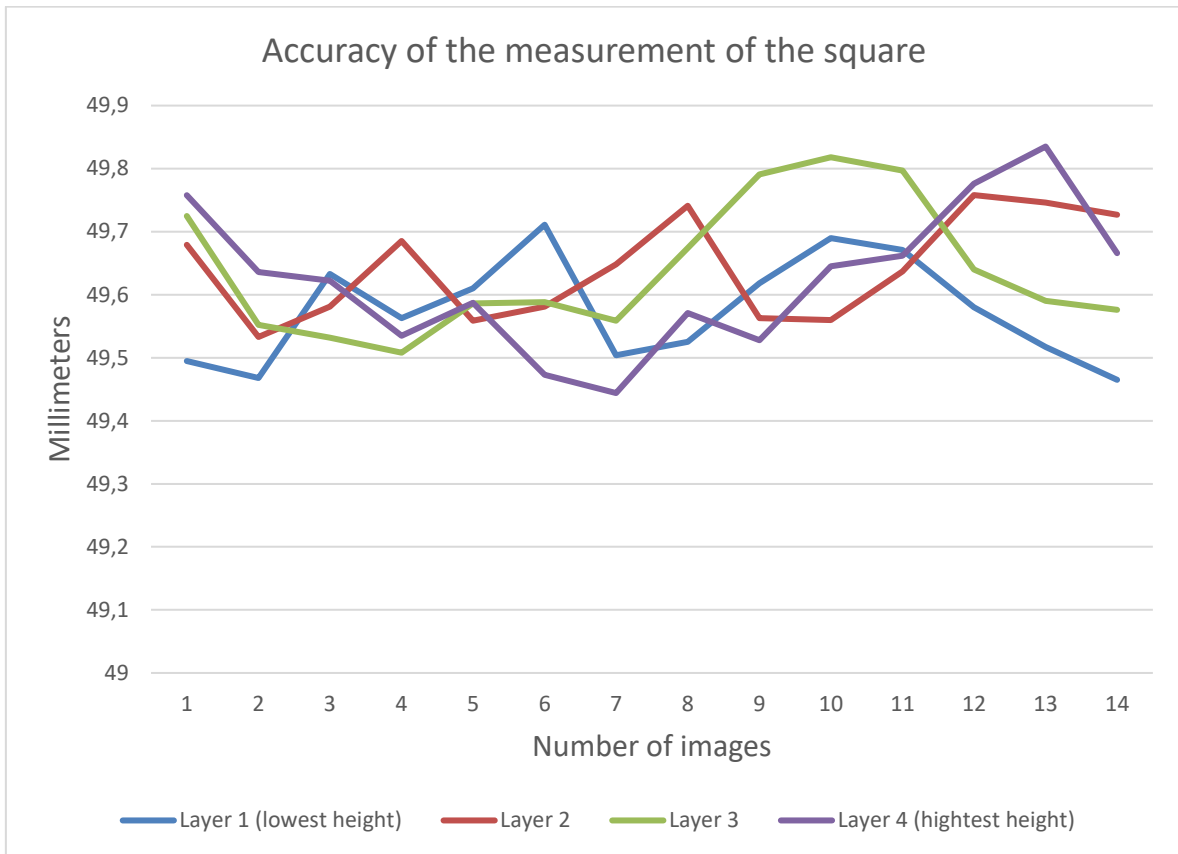


Figure 20. How accurately does the robot see the 50 mm * 50 mm square, on different layers, at the height-adjustable desk.

In the above figure, there are some variations, but when taking into consideration that it is an accuracy of 0,56 mm from 50 mm * 50 mm, and the distance is over one meter, it is very accurate.

The other important data from the images is the distance in pixels, measuring how many pixels the camera finds in the square, this varies depending on the height of the adjustable desk, and how accurately the camera sees the square. The goal is that the data from the pictures on a layer does not separate much. From the next figure, it can be seen the number of pixels in the square from the different layers at the desk setup. For all four layers, the difference between the pictures from a layer is only around two pixels, making it very accurate.

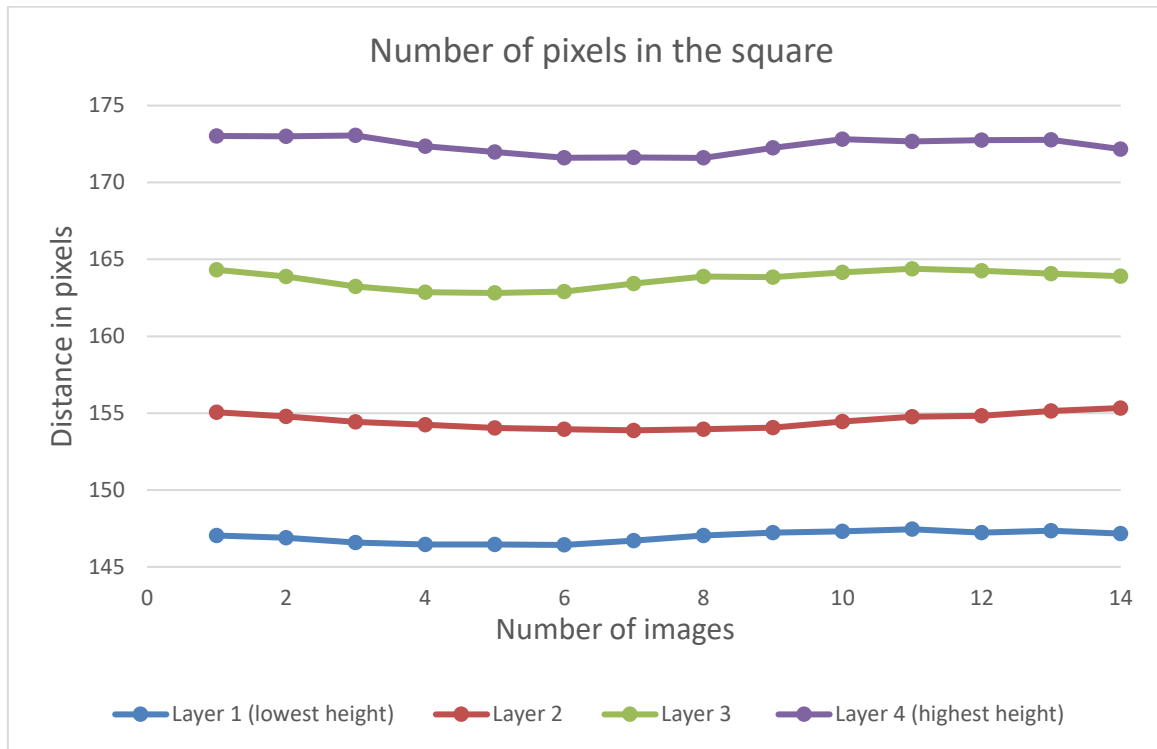


Figure 21. The number of pixels seen in the square.

The closer the calibration grid was to the camera, the better the calibration score was, especially when measuring the distance in pixels which measures how many pixels the camera sees inside the square. In the calibrations, the most important parameters that were measured were the distance in millimeters and the distance in pixels. The camera managed to find the square every time, on every layer, with similar accuracy. The main difference was the number of pixels the camera found in the square. The number of pixels increased every time the table was raised, and the increase in pixels was 18% more in the highest layer compared to the lowest layer. This is quite a significant increase in the number of pixel density.

5.2 Implementation in the production line

The same type of calibration was then used in practice in the production line, for each layer. When the cardboard box was filled, five images were taken with the same black square paper used for the manual calibration of the camera. One in each corner, and one in the middle of the box. When the robot had picked up all poles from the first layer, the same images were taken on the next layer, and then the third, and fourth layers.

This then gave data, for how accurate this type of calibration is, in practice.

	A	B	C	D	E	F	G	H	I
165									
166	Layer 3								
167									
168	Patterns	1.000							
169									
170		Index	Row	Col	Angle	Scale	Score		
171	Patterns	0.000		313.752	878.064	-0.942	100.014	99.997	
172									
173	Pixel								
174		Row0	Col0	Row1	Col1	Score			
175	Edges	259.546		823.545	361.531	821.707	-80.159		
176	Edges	363.428		933.467	263.443	935.253	-88.284		
177									
178		Row0	Col0	Row1	Col1	Angle	Distance		
179	Dist	310.538		822.626	313.435	934.360	88.515	111.772	
180									
181	Millimeter								
182		Row0	Col0	Row1	Col1	Score			
183	Edges	264.784		102.906	264.869	146.754	-82.584		
184	Edges	214.542		147.738	214.446	99.884	-87.510		
185									
186		Row0	Col0	Row1	Col1	Angle	Distance		
187	Dist	264.826		124.830	214.494	123.811	-178.840	50.343	
188									
189									

Figure 22. Calibration data from the production line.



Figure 23. Frames in the cardboard box, the second layer of frames is visible. The white A4 paper with the black square gets moved around the corners and midpoint.

As seen from figure 23, this calibration method is similarly accurate in practice, at the production line, as in theory with the height-adjustable desk. The camera manages to see the 50 mm * 50 mm square with an accuracy of 50,16 mm —50,70 mm, making an accuracy of 0,7 mm from the desired measurement of the square (50 mm * 50 mm). Since the camera at the production line can see the square being moved around, with similar accuracy as at the desk, this calibration method can be used.

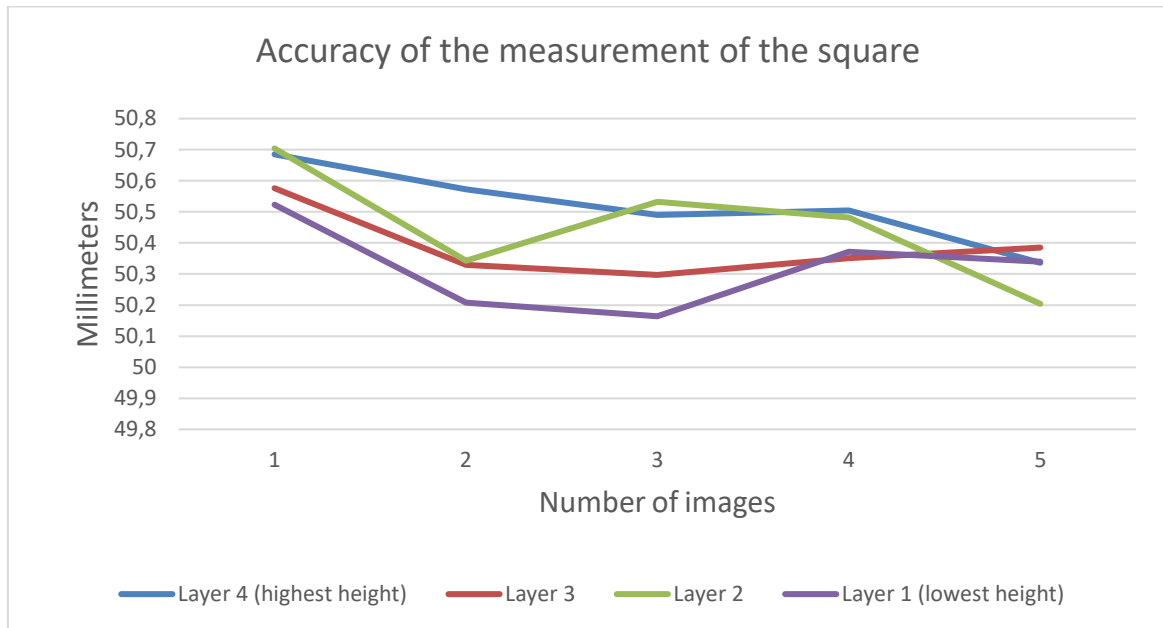


Figure 24. How accurately the robot sees the measurements of the 50 mm * 50 mm square, on different layers, at the production line.

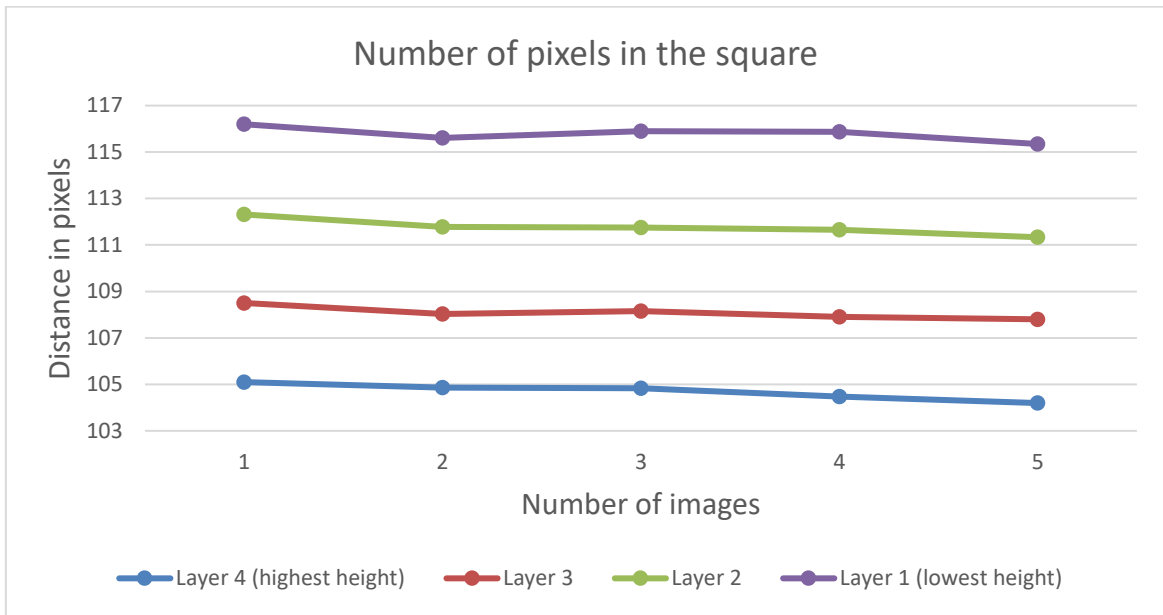


Figure 25. The number of pixels seen in the square, at the production line.

5.3 Personal reflections

As seen from the accuracy graphs (see Figure 20, 24) from the square's measurements, there is similar accuracy. This means this method is as good in practice as in theory, from an accuracy standpoint. The camera knows where the square or pole is in pixels and can connect the real-world coordinates of the robot with them.

At the current calibration method, the total number of feature points is what is being measured. In the calibration method implemented, how accurately the camera sees a specific object (the black square) is measured. These things are not the same, but it still gives a good understanding of accuracy.

There are other things to consider when comparing this calibration method with the current calibration method of the robot's camera, such as reliability, time consumed, and operability.

This calibration can be done more frequently since it is not as time-consuming as the calibration of the robot's camera where an empty box is being used, that manually gets filled, and the whole production line is at pause. That method also includes lots of manual work by hand, which increases the possibility of errors.

With the old calibration method, the camera searches for the hole in the frame for the switch. Many parameters can make the measurements more inaccurate, such as shadows, light, angles, and how precisely the frames are placed. The old method may require between one and two hours. The square calibration method does not take much longer than 10 minutes of additional time, since the production does not stop, it just pauses for every layer and quickly five pictures get taken by the robot's camera, that a person is operating, by moving the paper with the black square around the corners and to the middle of the box.

6 Discussion and conclusion

The purpose of this thesis was to find an alternative calibration method, that can improve the efficiency of the camera of the robot that picks up frames at one of ABB: 's production lines. An alternative calibration method was tested, both in simulation and in practice, and it gave accurate results. The current calibration method used is accurate but time-consuming. The biggest improvement with the new alternative method was the time-savings that the method brought. The second improvement was the operability, how easy it is for the operator to do the calibration.

The calibration process tested in this thesis can be implemented into the production line. The tests and data from them have proven that this method could get the robot to find the frames efficiently without complications.

There are always improvements to be made. For this operation, making the calibration method more automated would be the main thing to focus on. For instance, having the robot use some type of paper with either a black square or a circle would be ideal. The robot could with some type of jig be able to move around the paper or frame. Then the calibration process could be very quick, and could be done often, and would be easy to teach for the operators supervising the production line.

Lastly, I would like to thank ABB for giving me this opportunity to do my thesis for them. I also want to thank the Smart Power team for making it possible to do this thesis and make the calibrations at the production line and in the office. I want to especially thank my supervisor Tobias Mäenpää from ABB, for being very supportive and always giving me tips and ideas, and always having solutions for different complications.

I would also like to thank Leif Backlund from Novia University of Applied Sciences, who has been my supervisor for this thesis. His feedback and tips have helped me with my work. I have also received fast responses from him whenever I had questions related to the thesis.

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