



TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta mechatroniky, informatiky
a mezioborových studií ■

Rozpoznání obrobků kamerovým systémem – bin picking

Diplomová práce

Studijní program: N2612 – Elektrotechnika a informatika
Studijním obor: 3906T001 - Mechatronics

Autor práce: **Bc. Jan Kupeček**
Vedoucí práce: Prof. Dr. rer. nat. Stefan Bischoff
Konzultant práce: Dipl.-Ing. Fritz Klenk





TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Mechatronics, Informatics
and Interdisciplinary Studies ■

Part recognition with camera system – bin picking

Master thesis

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Author: **Bc. Jan Kupeček**
Supervisor: Prof. Dr. rer. nat. Stefan Bischoff
Counsellor: Dipl.-Ing. Fritz Klenk



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First name and surname: **Bc. Jan Kupeček**
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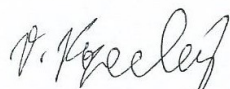
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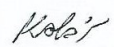
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Tutor for dissertation: **prof. RNDr. Stefan Bischoff**
Hochschule Zittau/Görlitz, IPM, Germany
Dissertation Counsellor: **Ralf Fein**
FLT GmbH, Hassmersheim, Germany
Other Counsellors: **Fritz Klenk**
FLT GmbH, Hassmersheim, Germany
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prof. Ing. Václav Kopecký, CSc.
Dean




doc. Ing. Milan Kolář, CSc.
Department Manager

Liberec, dated: 1 December 2014

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Abstract

This Master thesis is primary focused on current 3D vision technology and industrial bin picking. Here are compared different 3D image acquisition methods and their range of possibilities. Furthermore are discussed possible robotic cell configurations and comparison of several manufacturers of 3D cameras. Also here is described practical application of 3D vision together with Kuka robot on a bin picking task. In this application is camera used to detect aluminium profiles in a box and deliver coordinates of the most suitable profile to pick. For communication between the robot and the camera is used OPC server.

Part of this work is focused on barcode and data matrix code reading in industry. You can also find here potential problems connected with image acquisition.

This work was created in company Fibro Lápplé Technology.

Key words

Bin picking, industrial vision, 3D vision, object localization, lighting conditions, vision library, OPC communication, camera calibration, FLT, Kuka, Halcon, Ensenso, Data Matrix code reading

Abstrakt

Tato diplomová práce je zejména zaměřena na současnou 3D obrazovou technologii a průmyslovou aplikaci bin picking (úchop v bedně). Jsou zde srovnány různé technologie 3D zachycení obrazu a jejich rozsah možností. Dále jsou zde probrány možné konfigurace robotického pracoviště a porovnání různých výrobců 3D kamer. Také je zde popsána praktická aplikace 3D vidění spolu s Kuka robotem. V této aplikaci je kamera využita k rozpoznání hliníkových obrobků uvnitř bedny a následně jsou odeslány souřadnice obrobku nejvhodnějšího k vyzvednutí. Pro komunikaci mezi robotem a kamerou je použit OPC server.

Část této práce je zaměřena na rozpoznání čárových a maticových kódů v průmyslu. Také zde lze nalézt potenciální problémy spojené se zachycením obrazu.

Tato práce byla vytvořena ve společnosti Fibro Lapple Technology.

Klíčová slova

Bin picking, průmyslové vidění, 3D vidění, lokalizace výrobku, osvětlovací podmínky, vision knihovna, OPC komunikace, kalibrace kamery, FLT, Kuka, Halcon, Ensenso, čtení maticových kódů

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List of shortcuts

FLT	Fibro Lämppe Technology
OCR	Optical char recognition
TOF	Time of flight
DFF	Depth from focus
SNR	Signal to noise ratio
OLE	Object linking and embedding
OPC	OLE for process control

1 Introduction

1.1 Company FLT

Following work was created in company Fibro Läßple Technology GmbH (hereinafter FLT). Company FLT is member of a Läßple group which involves companies Läßple Blechverarbeitung GmbH, Fibro GmbH, Läßple Ausbildung GmbH and finally Fibro Läßple Technology GmbH. Whole group has over 2000 employees in Germany, Canada, USA and China.

FLT develops and builds rotary units, grippers, linear axis and gantries. Company is also manufacturer of turn-key industrial automation and can deliver complete solutions for automotive, mechanical engineering or general industry. Headquarters of FLT is in Haßmersheim (Baden-Württemberg).

History of FLT goes back to 1919 and men called August Läßple who founded his locksmith in Weinsberg: [1]

- 1919 - Founding of a mechanics workshop by August Läßple (1885-1968) in Weinsberg
- 1948 - LÄPPLE becomes first supplier of Porsche
- 1950 - Move to the new factory in Heilbronn
- 1958 - LÄPPLE is largest independent toolmaker in Germany with over 1300 employees
- 1994 - Takeover of FIBRO GmbH
- 1990 - Founding of LÄPPLE Blechverarbeitung GmbH & Co. KG Bayern in Teublitz
- 2002 - Founding of LÄPPLE AG
- 2004 - Acquisition of GSA Automation in Bad Friedrichshall and merger into FIBRO – GSA Automation
- 2009 - Founding of LÄPPPLE Blechverarbeitung GmbH Heilbronn
- 2011 - Merger of FIBRO – GSA and LÄPPLE Anlagenbau into FIBRO LÄPPLE TECHNOLOGY headquarters in Haßmersheim



Figure 1 - FLT Headquarters in Haßmersheim [11]

1.2 Bin picking task

“Take a toy out of a box” - very simple task which every child can solve, however it took decades of development to create vision systems advanced enough to manage this bin picking problem. History of machine vision goes back to 1950’s and 1960’s where theoretical basics and many algorithms that are still in service were developed. [2] In 1970’s machine vision started to be discipline of its own and the theory started to take shape in practical applications like barcode reading. In 1980’s it started to spread on new territories such as OCR or simple pattern recognition. Since 1990’s costs started to drop and machine vision becomes common part of industry. [3]

Today’s vision systems allows part detection, tracking, inspection, measurements, and of course – robot guidance. Current technology and manufacturers provides 3D cameras fast enough and vision libraries robust enough to solve bin picking task. Therefore this task is no longer an automation problem but another situation.

2 3D Camera technologies

There are several ways how to reach 2,5D and 3D image. The technologies differ in accuracy, scanning speed, range of use and of course price. I will mention also 2,5D techniques which are suitable for simple bin picking applications, but generally talking for robust bin picking task is essential to work with full 3D vision.

2.1 2,5D Vision

For some application (e.g. simple depalletization or applications with Scara robot) it is not necessary to work with full 3D vision because the robot cannot reach all 6 degrees of freedom anyway. Therefore the task can be achieved equally well with 2,5D vision. This requires only simple 2D camera because the “extra 0,5 dimension” can be reached by external device (such as proximity switch) or implicitly from image with methods available in used vision library. The methods use calibrated 2D camera and perspective distortion to achieve position vector of workpieces. There are two major ways how you can get this position, either by calibration of the camera in known distance or by working with a CAD model of your workpieces.

2.1.1 Calibration in known distance

In this method you calibrate a camera in the same distance and plane where you create pattern to search. Therefore the vision library knows a scale of the camera image and default orientation of your workpieces. With such data it can estimate 3D pose just from 2D image using a perspective distortion of the pattern.

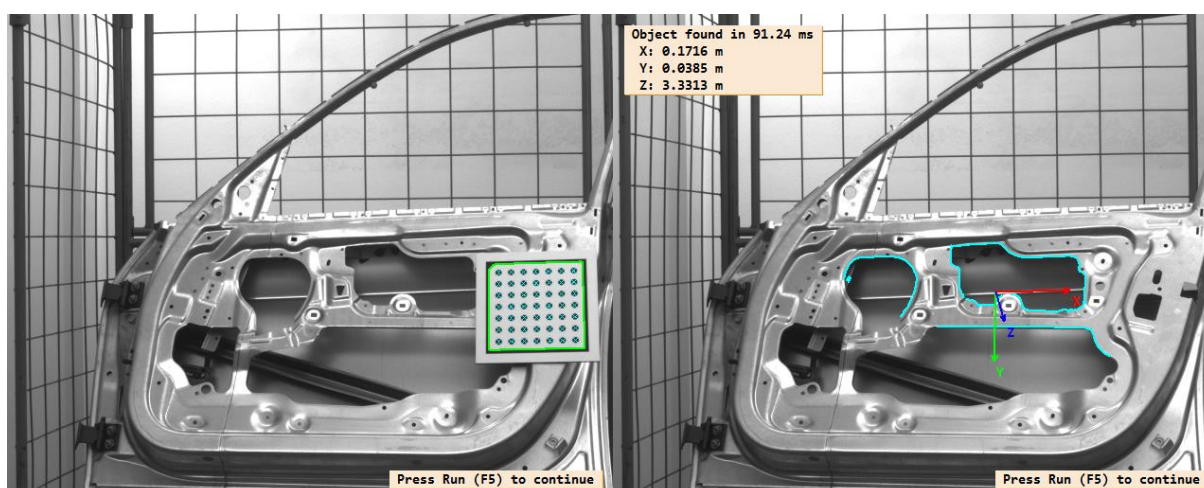


Figure 2 - Calibration in known distance [12]

2.1.2 Search for a CAD model

This method requires knowing of basic specification of used camera and lens. You must determine focus distance of your lens, lens distortion, physical size of camera pixels and camera resolution, then load this setting into vision library. Also you import a CAD model of your workpiece with known scale. The vision algorithm than can search for known edges of the CAD model, when a pattern is found the vision algorithm determines position of the workpiece in 3D based on predefined camera and lens setting.

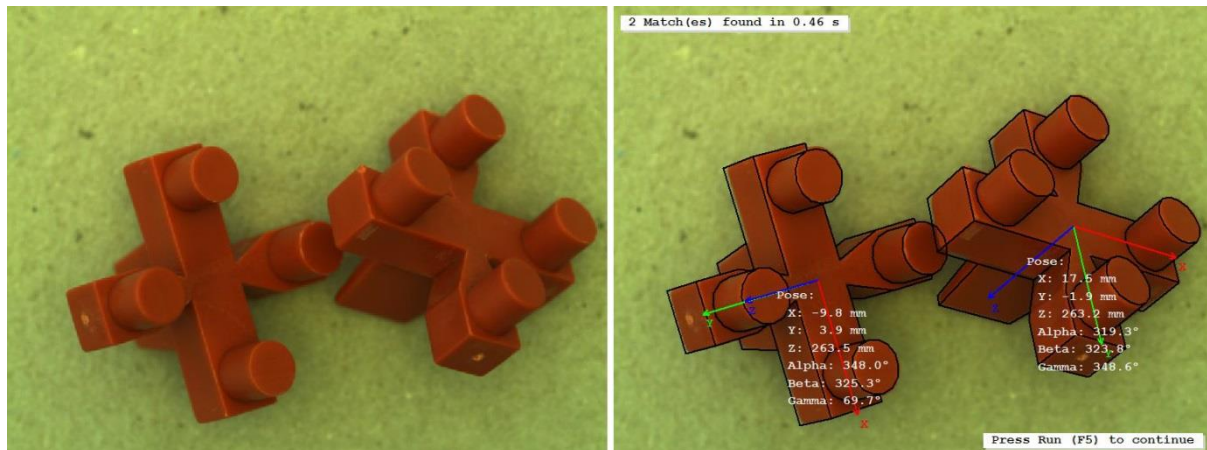


Figure 3 - CAD model recognition [13]

2.2 3D Vision

When the task requires actual 3D image there is whole spectrum of different methods how to achieve it. I will describe the most common.

2.2.1 Stereo matching

Stereo matching or multi-view matching determines surface image from two or more 2D images taken from different angles. Every camera involved in 3D image construction must be precalibrated so the vision library knows mutual position between each camera and can perform triangulation. You can achieve 3D image either by “passive method” or “active method”, however the principle is the same.

In order to triangulate the imaged points we need to identify corresponding image parts in the left and right image. Considering a small image patch from the left image, we could simply search the entire right image for a sufficiently good match. This would be too time-consuming to be done in real time. In fact geometry of the two projective cameras allows restricting the search to a one dimensional line in the right image, the so called epipolar line. For each pixel in the left image, we can now search for the pixel on the same scanline in the right image, which captured the same object point. If a sufficiently good and unique match was found, we associate the left image pixel with the corresponding right image pixel. The association is stored in the disparity map in form of

an offset between the pixels x-positions. The values in the disparity map encode the offset in pixels, where the corresponding location was found in the right image. We can then again use the camera geometry obtained during calibration to convert the pixel based disparity values into actual metric X, Y and Z coordinates for every pixel. [4]

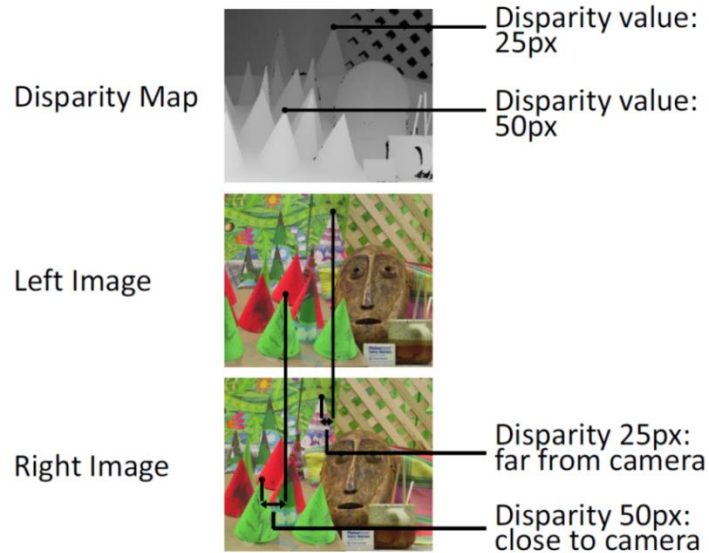


Figure 4 - Disparity image [14]

2.2.1.1 Passive method

The passive method computes the disparity map from basic images and does not use any artificial projection on the surface. Results from this method are sufficient only if used images have good contrast and also contrast between objects on the scene sufficiently differs. To determine what is sufficient difference is necessary to do testing on customer specific application. However it is clear that “white workpieces on white background” most likely will not work, on following picture is displayed 3D image (coloured) created by the passive method.

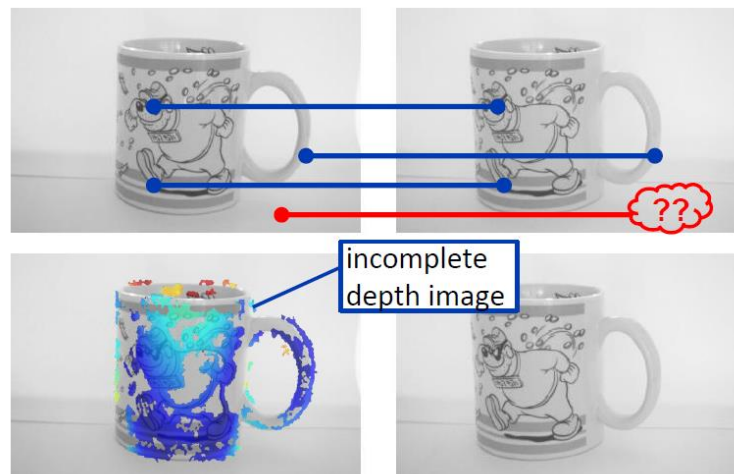


Figure 5 - Stereo vision passive method [15]

2.2.1.2 Active method

This method uses projection of artificial pattern on surface of workpieces and creates a disparity map from the thus obtained images. Important is that the pattern used for this method can be random and does not have to be known in advance. It is only used to create artificial contrast points on the surface which helps with creation of the disparity map.

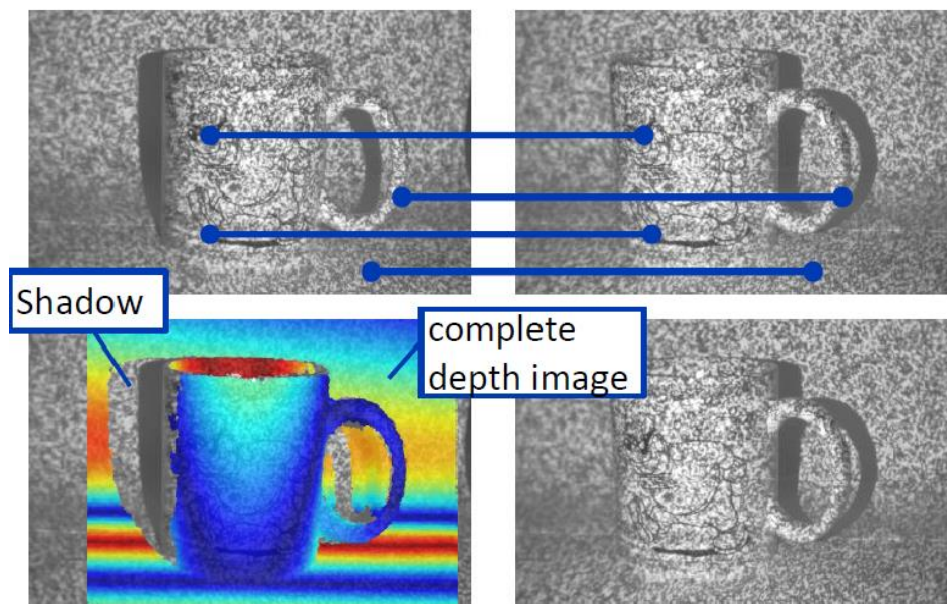


Figure 6 – Stereo vision active method [16]

2.2.2 Time of flight

Time of flight cameras (hereinafter TOF) provide 3D image at very high speeds. They are capable to reach framerate up to 160 fps. [5] However this velocity is redeemed by significantly lower image resolution which currently achieves up to 352x288 pixels. [6] [7]

TOF camera works by illuminating the scene with a modulated light source, and observing the reflected light. The phase shift between the illumination and the reflection is measured and translated to distance. Typically, the illumination is from a solid-state laser or a LED operating in the near-infrared range (~850nm). Note that the light entering the sensor has an ambient component and a reflected component. Distance (depth) information is only embedded in the reflected component. Therefore, high ambient component reduces the signal to noise ratio (SNR). [8]

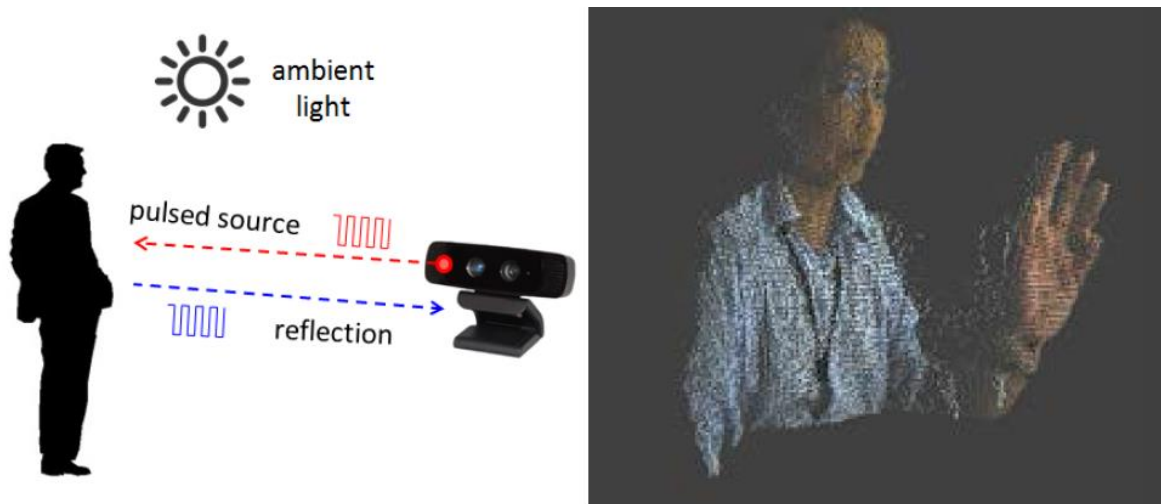


Figure 7 - TOF camera principle and image [17] [18]

2.2.3 Laser scanner

Laser triangulation reconstructs the surface of a 3D object by approximating it via a set of height profiles. The idea of the sheet-of-light technique is to project a thin luminous straight line, e.g. generated by a laser line projector, onto the surface of the object that is to be reconstructed and then image the projected line with a camera. The optical axis of the camera and the light plane form an angle α , which is called angle of triangulation. The points of intersection between the laser line and the camera view depend on the height of the object. Thus, if the object onto which the laser line is projected differs in height, the line is not imaged as a straight line but represents a profile of the object. To reconstruct the whole surface of an object, the object must be moved relative to the measurement system. [9]

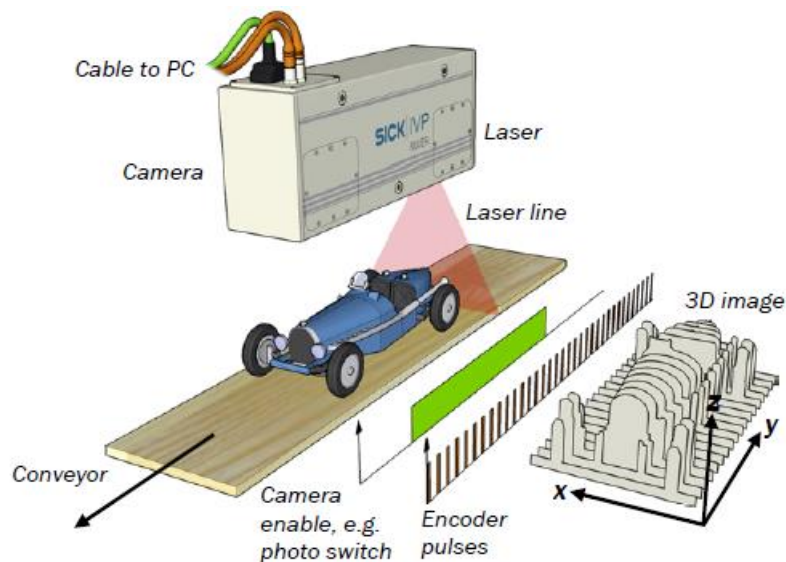


Figure 8 - Laser scanner principle [19]

There are two concepts of laser scanning available. Either a laser beam is projected directly on surface and whole set of the camera and laser move relatively to

workpieces. Essential for getting authentic 3D image with relative moving camera is to synchronize speed between relative camera movement and camera triggering. Second choice is to use static camera with laser beam which is projected on a mirror. Then only the mirror moves inside a chassis and reflects laser beam across whole field of view.

Main problem of surface scanning with laser scanners is no-data areas behind steep edges. These areas can be reduced by using smaller angle of triangulation but it is not recommended to work with angle lower than 30° due to decreasing accuracy. On the other hand it is also not recommended to work with angle wider than 60° because the accuracy of laser system will be decreased by „thickness“ of the laser beam itself.

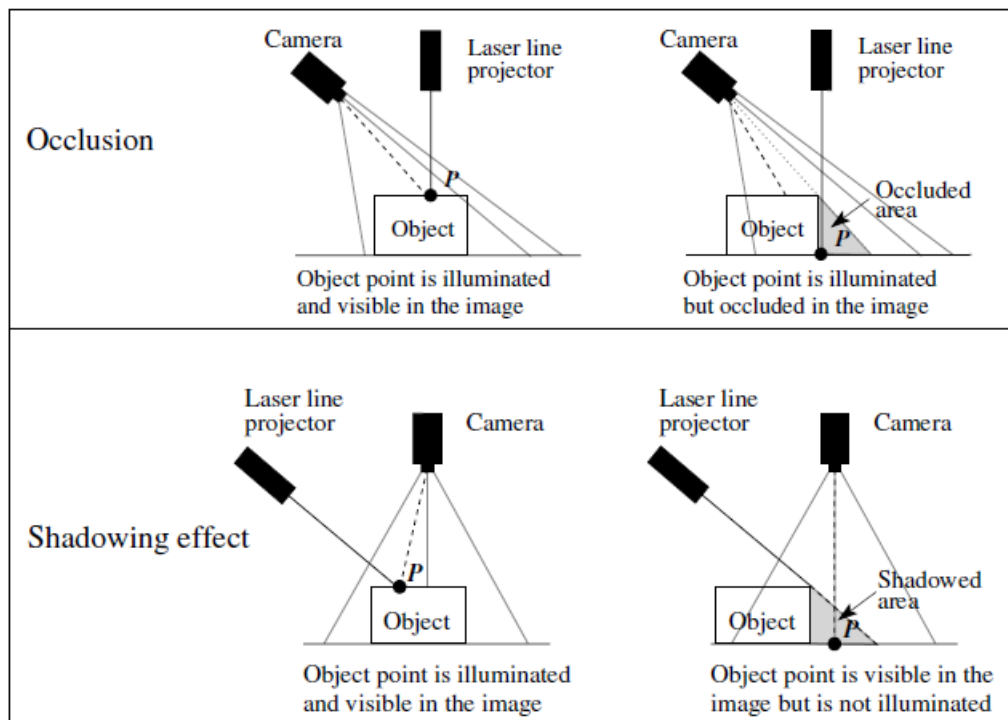


Figure 9 - Laser scanner shadow problem [20]

2.2.4 Depth from focus

This is very accurate method of capturing 3D image and which allows getting more accurate results than stereo vision or laser scanning techniques. But because it requires telecentric or microscope lens, the method is suitable only for small workpieces (e.g. SMD components). This technique requires only one camera which takes several images in different distances to the surface. To change the distance you can either move with the whole camera or just with the focus.

With depth from focus (DFF) you can reconstruct the surface of a 3D object based on the knowledge that object points have different distances to the camera and the camera has a limited depth of field. Depending on the distance and the focus, object points are displayed more or less sharply in the image, i.e., only those pixels within the correct distance to the camera are focused. Taking images with various object distances, each object point can be displayed sharply in at least one image. Such a sequence of images is

called “focus stack”. By determining in which image an object point is in focus, i.e., sharply imaged, the distance of each object point to the camera can be calculated. [9]

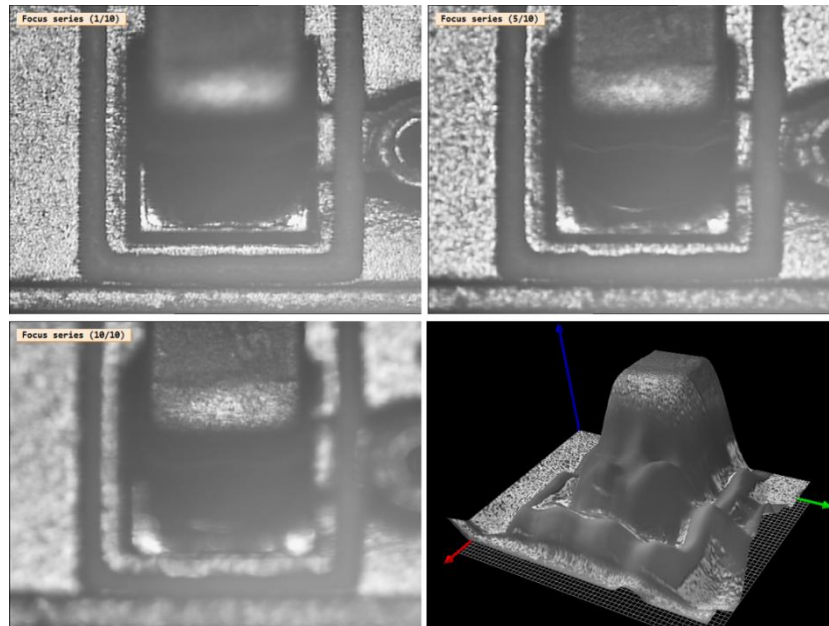


Figure 10 - Depth from focus [21]

2.2.5 Fringe projection

Next common method is fringe projection on a surface and then determining the 3D image from curvature of the stripes. Principally this method combines laser triangulation with active stereo vision, however, because it is using known and calibrated pattern, it can capture the surface image with using of just one camera. Pattern is created by parallel lines which are projected on whole field of view; therefore the surface image can be created at once. However it is possible to gain fidelity of the 3D image by capturing of several images with shifted pattern or even projecting pattenr perpendicularly. But such procedures require avoiding of any movement between sequential image capturing.

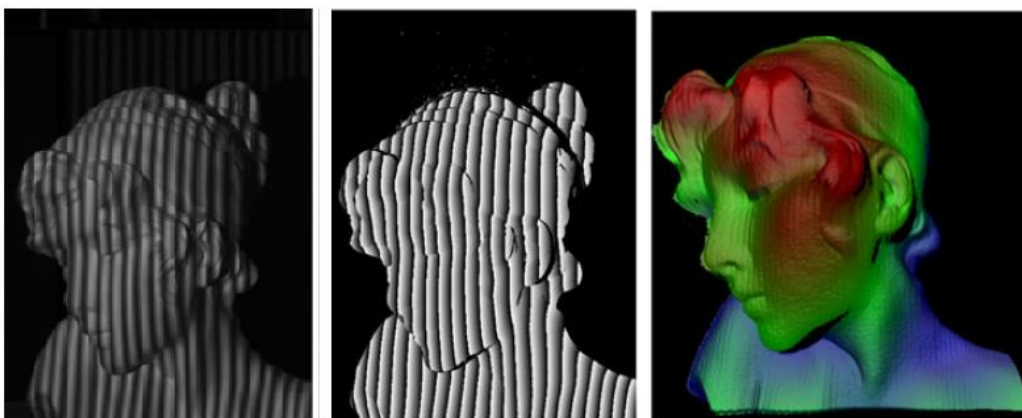


Figure 11 - Fringe projection [22]

3 Possible configurations

Crucial for successful bin picking is to choose appropriate 3D image technology, however to get answer on this question you face a lot of others. What is size of workpieces? How to grip them? What is desired accuracy? How to deal with surrounding lighting... Therefore there are many robotic cell concepts possible and the specification depends as always on given task. However mostly common for bin picking is to work with laser scanners or pattern projecting cameras and basic division of configurations is following.

3.1 External camera configuration

Camera is mounted on external stand above the box with workpieces. Based on chosen technology the camera have to move or not. Pattern projective cameras and mirror-using laser scanners can be static so you don't lose any accuracy arising from small position changes of a dynamic camera solution. Also you save costs for additional axis which would be necessary for the dynamic camera, but from this point it is hard to say if you also save costs of the whole vision solution. It is because these advanced cameras are more expensive within a production range of one manufacturer. With external camera configuration robot gets more freedom in picking orientation, especially when a tall box is used, because the robot gripper without the camera can be smaller and therefore more agile. You only must protect the camera only against the robot's body which can be done by creating a safe zone in which the robot cannot go.

On the left image is a static configuration with laser scanner which uses mirror, here no additional axis is necessary. Configuration on the right is using laser scanner which requires external axis for surface scanning.

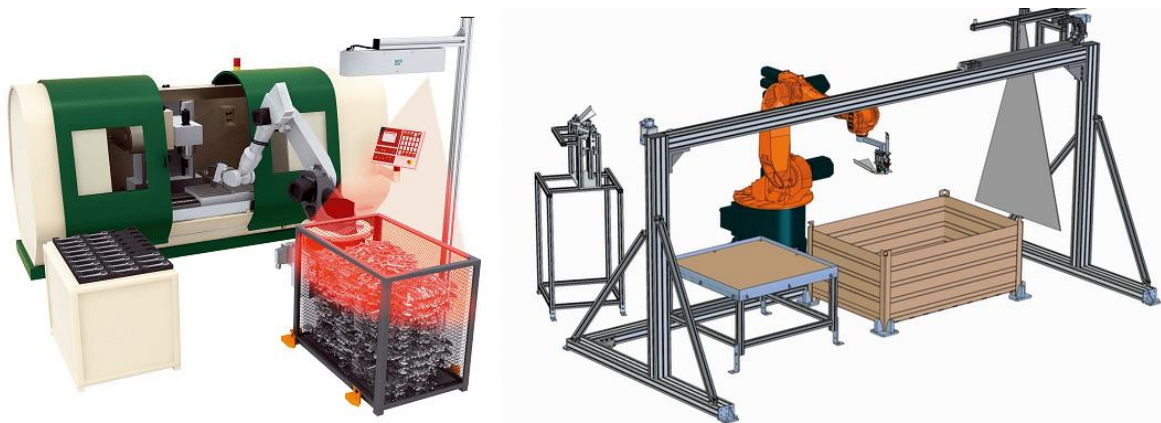


Figure 12 – External camera solution [23] [24]

3.2 Robot-mounted camera configuration

Alternative is to attach the camera on the robot. This method on the other hand provides programmer more freedom with troubleshooting of workpieces localization, e.g. when workpieces cannot be detected or detection is not robust, robot can easily decrease distance or change angle to the surface and camera system can try it again. It also allows easy implementation of multi-view method for creation of surface image by using just one camera and different capture angles, such system will have very good price/performance ratio. When laser scanner is used, linear movement can be done by robot itself. However disadvantage of these methods is decreased accuracy which comes from limited repeatability and path accuracy of robot movement.

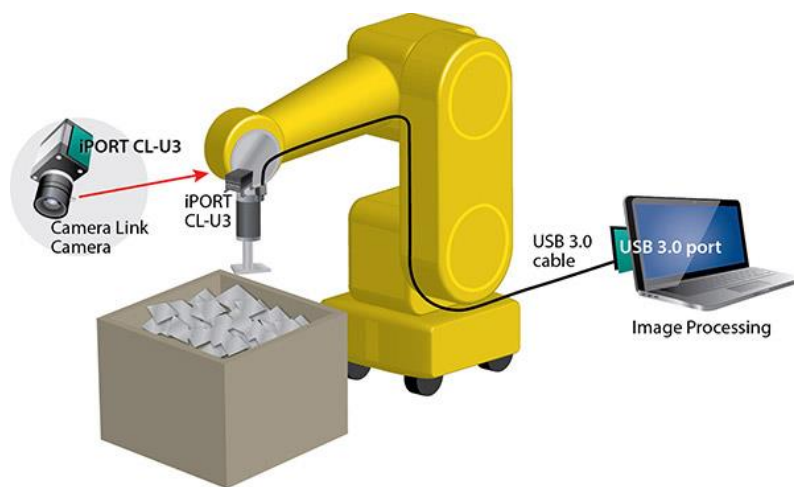


Figure 13 – Robot-mounted camera solution [25]

4 Manufactures

Machine vision market can be sorted into several categories. We can sort manufactures either by a range of their applications:

- Barcode scanners/readers – use laser/camera to identify 1D code only
- Datamatrix readers – use camera to identify 1D and 2D codes
- Vision sensors (smart cameras) – all-in-one solution (camera, optics, processor, lighting) which can be used for basic identification, inspection or measurement, includes also basic 3D sensors
- Vision systems – for difficult tasks (robot guiding, high speed applications, monitoring of traffic..), can use industrial PC for image processing

By range of their products:

- Cameras without own vision library – cameras are equipped only with drivers and interface to common vision libraries
- Cameras with their own vision library – cameras are delivered together with appropriate vision library from the same manufacturer
- Vision libraries only – producers of software for image recognition

Or by range of their work:

- Camera or vision library dealers only – companies that only sell their products and provide technical support
- Vision solution integrators – companies that delivers complete vision part of the task (this mainly contains installation of appropriate camera, lighting and vision program)
- Complete solutions integrators – companies that delivers turn-key solution of whole task (this means vision solution together with installation of e.g. belt conveyor, robotic cell, welding gun, etc.)

Following manufacturers were chosen by company FLT for more detailed investigation.

4.1 Vitronic

4.1.1 Aim of the company

- Manufacturer of traffic cameras and body scanners, integrator of industrial vision systems
- 2D capabilities: robot guiding, surface inspection, cylinder inspection, gauging, code reading applications, logistics, also health care and traffic monitoring
- 3D capabilities: 3D welding inspection, 3D volume inspection (with their own cameras)
- Not a lot of 3D guiding; it is only possible with prepositioning

4.1.2 Production

- Built line cameras, 3D volume inspection cameras, 3D welding inspection cameras, also small amount of matrix cameras (but they usually buy matrix cameras)
- Also lighting manufacturer
- Use their own vision library (included in price of cameras)
- They deliver only turn-key solutions (with their camera, SW and lighting), don't sell cameras or SW separately (with one exception - „Snap camera“ is sold separately with SW interface for barcode reading).

4.1.3 Possibilities of bin picking

- Don't offer solution for random bin picking
- Viro2D – 2D guiding by their own vision library + camera
- Viro3D – 3D guiding need some prepositioning otherwise it does not work, for the task they use their own cameras.

Service depends on contract conditions, can be also 24/7.

4.2 ISRA

4.2.1 Aim of company

- Industrial integrator of vision systems
- 2D capabilities: robot guiding, surface inspection, gauging, code identification, OCR, glue inspection, logistics
- 3D capabilities: robot guiding, gauging, bin picking

4.2.2 Production

- Built their own cameras and use their own vision library (included in price of cameras)
- They can deliver whole turn-key solution or only camera and SW interface for step-by-step programming

4.2.3 Possibilities of bin picking

- Offers two systems which differs only in scanning time
- “Shapescan” LED scanner
 - Camera in static position (projector in middle project lines on surface and 2 cameras in corners recognize 3D shape)
 - Can use 3 or 7 lines (difference in reading time and price)
 - Scan time is 1,5 or 3,5 sec (depends on model)
 - Requires CAD model for part recognition
 - Accuracy is between 1-5 mm
 - Price starts at 32 000 Euro (camera, SW, cables, calibration, robot interface)

Service depends on service contract; it can be within 48 or 24 hours.

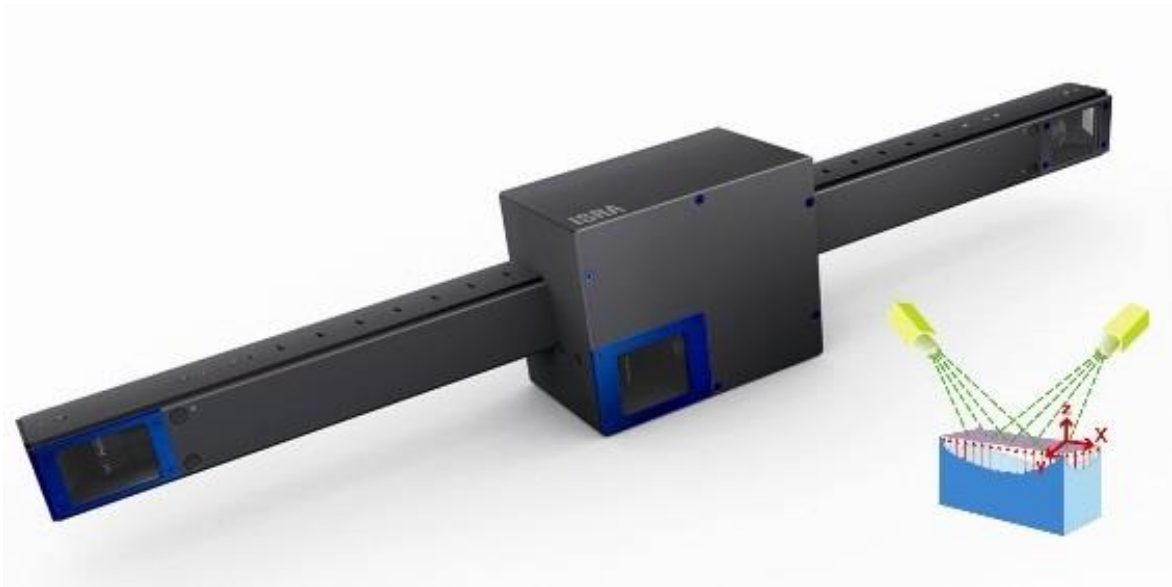


Figure 14 - ISRA Shapescan [26]

4.3 VMT (Peppri – Fuchs)

4.3.1 Aim of company

- Industrial integrator of vision systems
- 2D capabilities: robot guiding, surface inspection, gauging, code identification, OCR, glue inspection, gap measurement, logistics, health care
- 3D capabilities: robot guiding, glue inspection, gauging, bin picking

4.3.2 Production

- Use Peppri – Fuchs cameras, code readers and sensors if possible, if none of them is suitable then third-party (Sick, Cognex, IDS...)
- Use their own vision library
- Deliver turn-key vision solution, don't sell cameras or SW itself; although it might be possible to get training and do the vision programming in FLT.

4.3.3 Possibilities of bin picking

- They have references in VW with bin picking
- Can deliver whole solution
 - Use laser scanner on linear axle (scanning time ca. 2 seconds)

- Distance between camera and box can be 1-2 meters
- No additional lighting
- Price for vision solution would start on 42 000 Euro

Service depended on service contract, can also be 24/7.

4.4 Quiss

4.4.1 Aim of company

- Industrial integrator of vision systems
- 2D capabilities: robot guiding, surface inspection, cylinder inspection, gauging, glue inspection, code reading, OCR
- 3D capabilities: robot guiding, gauging, bin picking

4.4.2 Production

- Use own cameras and vision library
- Deliver only complete solution and integrate whole system, does not sell only camera or vision library.

4.4.3 Possibilities of bin picking

- Produces vision systems for 2D belt-picking or depalletization
- Can solve also bin picking task but at the time of my investigation they were busy with other project and did not provide any further information.

4.5 Engrotec

4.5.1 Aim of company

- Industrial machine vision integrator, roller hemming manufacturer and integrator
- 2D capabilities: robot guiding

- 3D capabilities: robot guiding, gauging, roller hemming inspection

4.5.2 Production

- Roller hemming tools
- Usually deliver complete solution with their cameras and vision software
- 3D Robot guiding is possible only with repositioning of parts

4.5.3 Possibilities of bin picking

- None of their cameras can handle bin picking task
- Their cameras might work with Halcon vision library, but it had never been tested

4.6 IDS

4.6.1 Aim of company

- Matrix camera manufacturer
- Distribution of Halcon vision library and exclusive distribution of Ensenso 3D cameras
- Training lessons with Halcon software

4.6.2 Production

- Built their own cameras (only buy chips – Sony, NIT, Aptina...)
- Don't have their own vision library – cooperates with MVTec (Halcon)
- Cameras have also interface for other vision libraries.
- Sell only cameras and Halcon SW, if customer wants integration they cooperate with company BS Automatisierung.

4.6.3 Possibilities of bin picking

- Have successful bin picking applications
- Ensenso N10 and N20 stereo camera can be used
 - Have 2 matrix cameras and pattern projector

- Resolution 0,5 – 2,3 mm (with reading distance 1000 mm)
- Programming through Halcon vision library or some other
- It might be necessary to use 2 cameras to get accurate image
- Price 8900 Euro (camera) + 5500 Euro (Halcon vision library)

Service support is available between Monday - Friday and 08:00 - 17:00.



Figure 15 - Ensenso N20 [27]

4.7 Sick

4.7.1 Aim of company

- Manufacturer of all kind of sensors for industrial application
- 2D capabilities: inspection, measurement, robot guiding, code identification, logistic, OCR
- 3D capabilities: inspection, measurement, bin picking

4.7.2 Production

- Use their own vision library
- Can deliver only camera or whole vision solution
- Offers many different 3D cameras, i.a. special vision system for bin picking and rack picking

4.7.3 Possibilities of bin picking

- Sick Ranger
 - Laser scanning system which requires relative movement between camera and box
 - Camera and laser are not built in one body
 - Scanning can be done simultaneously with near-infrared or RGB spectrum (depends on model)
 - Requires industrial PC for running of Sick vision library
 - Can be also working with 3rd party vision library
 - Price 10 000 – 17 000 Euro (depends on model, includes vision library)
- Sick PLB
 - Laser scanning system specially developed for bin picking (displayed on Figure 11 – left)
 - Using mirror for shifting of laser (no addition axis needed)
 - Delivered with bin picking library which only requires parametrization
 - Has integrated computer for running of vision programme
 - Price 25 000 Euro (includes vision library)



Figure 16 - Sick Color Ranger E [28]

4.8 Summary

If we will focus only on bin picking task then we can sort manufacturer's capabilities into following groups:

- No bin picking capability: Vitronic, Engrotec
- Camera and vision library dealers - ISRA, IDS, Sick
- Vision solution integrators – VMT, ISRA, IDS, Sick
- Complete solution integrators – Quiss, BS Automatisierung

5 Practical application

5.1 Task

Practical application was realized in production hall of company FLT – Haßmersheim. Task was to create bin picking solution with given workpieces and Kuka robot type KR 360-3 (range 2825 mm, payload 360 kg). Selected workpieces were shiny aluminium profiles with size of 180 x 100 x 50 mm. Maximum weight of profiles was 1kg. They were partially dirty and with scratches. Their shape also allowed small risk of entanglement.



Figure 17 - Aluminium workpiece

Workpieces were placed in a wooden box with size of 660 x 470 x 370 mm. Accuracy of camera should be lower than ± 3 mm in all directions due to gripping tolerance. Camera could be static or mounted on a robot, therefore the reading distance could vary between 500 mm to 2500 mm (according to selected camera). Target cycle time was 8 seconds per workpiece including snapping of image, image recognition, sending coordinates and robot picking.



Figure 18 - Robotic cell

5.1 Camera selection

Given task requires working with full 3D vision. First of all is necessary to select suitable camera technologies for the job. Because of high accuracy demand it is not suitable to work with TOF cameras which are currently not very precise. The size of the workpieces causes that DFF technology is also not suitable. And finally when we consider a fact that all workpieces are shiny and single-colored, passive stereo camera shouldn't be used either. Therefore for this task is suitable to use laser scanner (Sick or ISRA) or pattern projection camera (IDS-Ensenso).

All three manufacturers (Sick, ISRA and IDS) offer a 3D camera which fulfills requirements of this specific task (described in Chapter 4). Main advantage of Sick PLB and ISRA Shapescan vision systems is that they don't need to be programmed but only parametrized in a step-by-step user interface. The IDS – Ensenso N20 camera on the other hand delivers only 3D point cloud and requires external PC with 3rd party vision library for programming. After a consultation about possible borrowing of the cameras we have decided to use the Ensenso N20 for the task.

5.1.1 Ensenso N20 camera

Company IDS is an executive dealer of Ensenso cameras. Company Ensenso is camera manufacturer with two types of pattern projective cameras, those are types N10 and N20.

Both of these types are manufactured with many different lens settings and all these models cover wide range of focus distances, accuracies and fields of view. Differences between the basic camera models and range of lens settings are described in following table.

Table 1 - Ensenso models

	N10	N20
Resolution	752 x 480 px	1280 x 1024 px
Interface	USB 2.0	Ethernet
Power	USB bus	POE or External
Focal lengths	3 - 16 mm	6 - 16 mm
Colour	IR	IR or Blue
Dimensions	150 x 45 x 45 mm	175 x 50 x 50 mm

Required cycle speed demanded to scan whole surface at once. Therefore due to better accuracy and lower collision risk we have decided to use static camera configuration. Because of the size of a robot it was necessary to do the scanning from distance of 2000 mm. On Ensenso web pages is a special applet which helps customers to find appropriate camera for their task. For our task was recommended and approved by IDS to use model N20-1202-16. This camera has following specification.

Table 2 - N20-1202-16 specification

Minimum working distance	1100 mm
Maximum working distance	2200 mm
Optimum working distance	1400 mm
Focal length	12 mm
Mass	550 g
Vergence angle	2°
Resolution	1280 x 1024 px
f-number	1,6
Power consumption	9,5 W

Accuracy of selected camera from 2000 mm distance is 2,1 mm in Z axis and 0,85 mm in X and Y axis. Camera is able to reach framerate up to 30 fps, however this requires to decrease the image quality. With full resolution and maximum accuracy I was able to reach maximum framerate up to 5 fps.

During writing of the thesis were announced new cameras N30 and N35. Both types will have better protection housing and type N35 will also have better resolution, but no technical specification was released yet.

5.1.2 Halcon vision library

The camera programming had to be done through special vision library. I was using Halcon (version 12) from company MVTec. This vision library can be used for all kind of 1D, 2D and 3D vision tasks and also includes integrated communication interface for Ensenso cameras. Halcon has its own programming language and interface called HDevelop however it is also possible to work with common programming languages.

HDevelop is a tool box for building machine vision applications. It facilitates rapid prototyping by offering a highly interactive programming environment for developing and testing machine vision applications. Based on the HALCON library, it is a versatile machine vision package suitable for product development, research, and education. There are four basic ways to develop image analysis applications using HDevelop: [10]

- Rapid prototyping in the interactive environment HDevelop.
You can use HDevelop to find the optimal operators or parameters to solve your image analysis task, and then build the application using various programming languages, e.g., C, C++, C#, Visual Basic .NET, or Delphi.
- Development of an application that runs within HDevelop.
Using HDevelop, you can also develop a complete image analysis application and run it within the HDevelop environment.
- Execution of HDevelop programs or procedures using HDevEngine.
You can directly execute HDevelop programs or procedures from an application written in C++ or any language that can integrate .NET or COM objects using HDevEngine.
- Export of an application as C, C++, Visual Basic .NET, or C# source code

Finally, you can export an application developed in HDevelop as C, C++, Visual Basic .NET, or C# source code. This program can then be compiled and linked with the HALCON library so that it runs as a stand-alone (console) application.

I decided to create a camera program in HDevelop's native language. Development license of this vision library costs 5500 Euro and a runtime license costs ca. 700 to 1200 Euro (depends on included vision libraries).

During writing of the thesis company MVTec announced new vision software Merlic. This software will use Halcon vision library, but the actual programming will be replaced by step-by-step interface. This interface should be more user friendly and allow easier creation of vision programmes. However it will only be possible to create programmes for easier tasks such as code reading, measurement, inspection check etc. and it will not contain libraries for 3D applications.

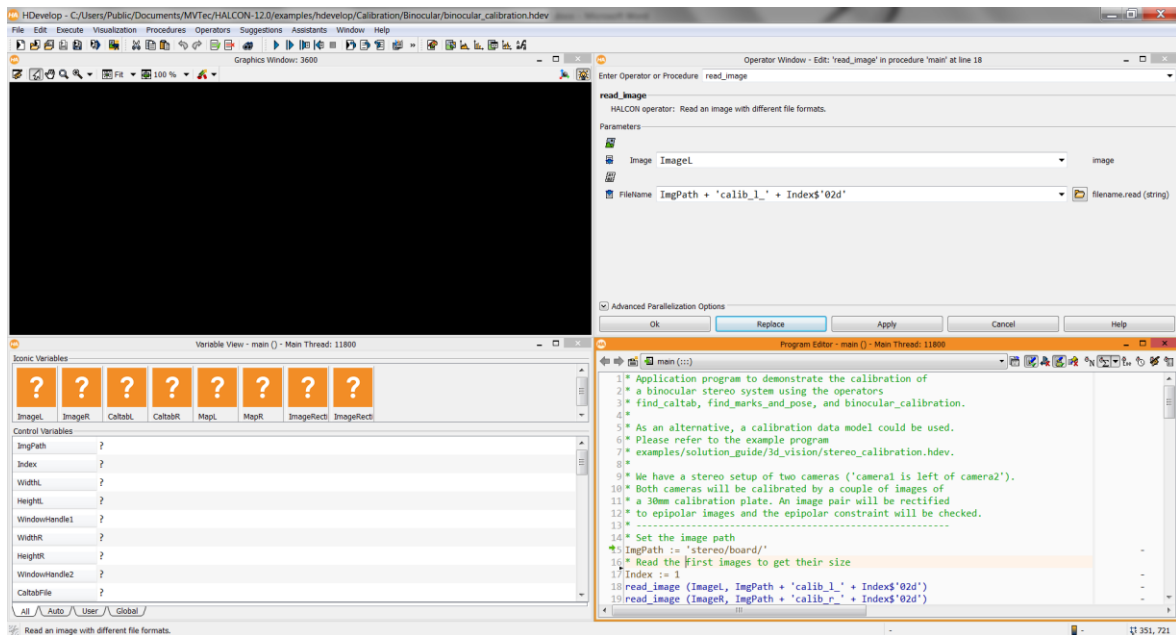


Figure 19 - HDevelop user interface

5.2 Gripper selection

When we consider a shape of workpieces, the simplest solution would be to use magnetic gripper, but due to a fact that the workpieces were made from aluminium I had to look for other way. First was necessary to determine gripping force with a simple calculation:

$$F = \frac{k * m(g + a)}{u}$$

Where k is safety factor, m is mass of the workpiece, g is gravitational acceleration, a is robot acceleration and u is coefficient of static friction.

5.2.1 Parameters

- Weight of workpiece: 0,8 – 1 kg (depends on inside profile)
- Overload during manipulation: 10 ms⁻²
- Necessary force: 40 – 160 N (depends gripping on technique and orientation)
- Ability to grip workpiece with tolerance ± 4 mm

5.2.2 Potential gripping techniques

- Clamps - Using of clamps is not suitable for these workpieces, because of their rectangular shape. In a situation where two of them were close to each other, there would be no room for the gripper to go.

- Vacuum cups - This solution provides easy gripping possibilities on the top of the workpiece. However because of narrow space in the middle it is necessary to use small vacuum cups in and compensate the force with a strong vacuum pump.
- Separate fingers – The idea is that the fingers would go into an inside gap of the top of the workpiece and bend itself. This solution would require also using a vacuum cup to avoid slip.
- Balloon gripper – Principle is the same like with the separate fingers but the grip would be provided by expanding balloon. This turned out to be not suitable because of small expansion difference and therefore small tolerance.



Figure 20 - Finger gripper and balloon gripper [29] [30]

Due to maximum collision protection and orientation possibilities I used two vacuum cups. Used vacuum pump was type Schmalz SMP 25 AS IRD SO which generated vacuum up to -850 mbar. It was connected to the Kuka robot controller through Interbus module. Gripper was also fitted with induction proximity switch type Pepperl + Fuchs NRB5-18GM50-E2-C-V1 which was placed between the vacuum cups. List of control variables and their port numbers in robot system is shown on tables.

Table 3 - Digital outputs

	Port number
Vacuum on/off	3370
Blow on/off	3369

Table 4 - Digital inputs

	Port number
Vacuum reached	3393
Vacuum below demanded level	3392
Proximity switch	3391

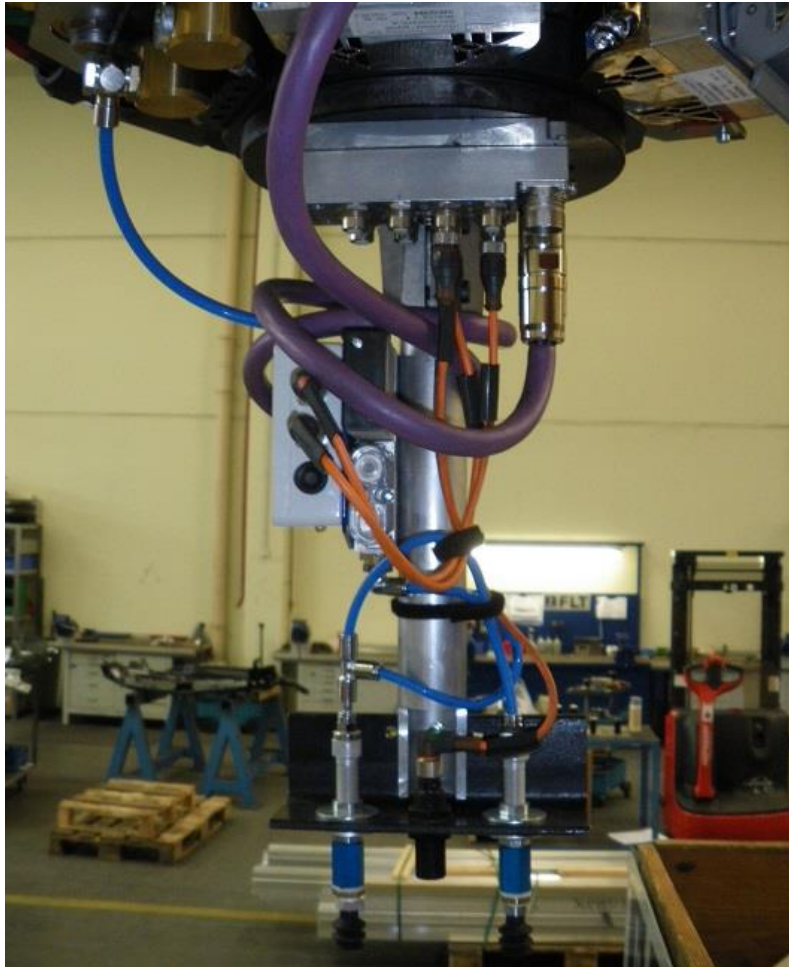


Figure 21 - Gripper

5.3 Communication

Key communication which transferred coordinates of workpieces suitable to pick and also managed synchronization between Halcon and Kuka program flow was done through OPC Server. I decided for OPC because it was natively supported by Halcon and also by Kuka. However I challenged an obstacle with PC security.

5.3.1 Kuka – Halcon communication

Halcon vision library has native interface for OPC communication, it allows to be connected as a client through OPC DA and OPC UA protocols. Also Kuka supports OPC in versions OPC DA and OPC DA-XML, but it is necessary to install and run the OPC Server on the Kuka controller. I was using Kuka OPC Server version 4.1.1. Therefore it theoretically shouldn't be a problem to establish communication between the systems through OPC DA protocol which they both have in common. However during the realization it turned out that PC that I was using were equipped with very strong antivirus protection which couldn't be turned off. No matter what setting of the PC or the Kaspersky antivirus I tried it did not allow establishing of direct communication through

the OPC DA protocol. Therefore I had to change communication to second protocol version which is supported by Kuka – the OPC DA-XML. This protocol version is using XML files for communication. Advantage of this solution is that it can avoid security protection issues because the Kaspersky antivirus system recognizes the XML file (which cannot cause any damage) and allows its transfer.

For a protocol conversion which allowed Halcon to communicate with Kuka I used external software from company Unified Automation called UaGateway. This software emulates virtual OPC UA server and allows Halcon vision library to connect on this server through Halcon’s native OPC UA client. UaGateway then connects to Kuka OPC DA-XML server as a DA-XML client (it also supports OPC DA, AE, HAD, and UA clients). Then it converts data between UA and DA-XML protocols and the communication is established. I was using a trial version with limitation of 1 hour of runtime. Full license of this software costs 500 Euro.

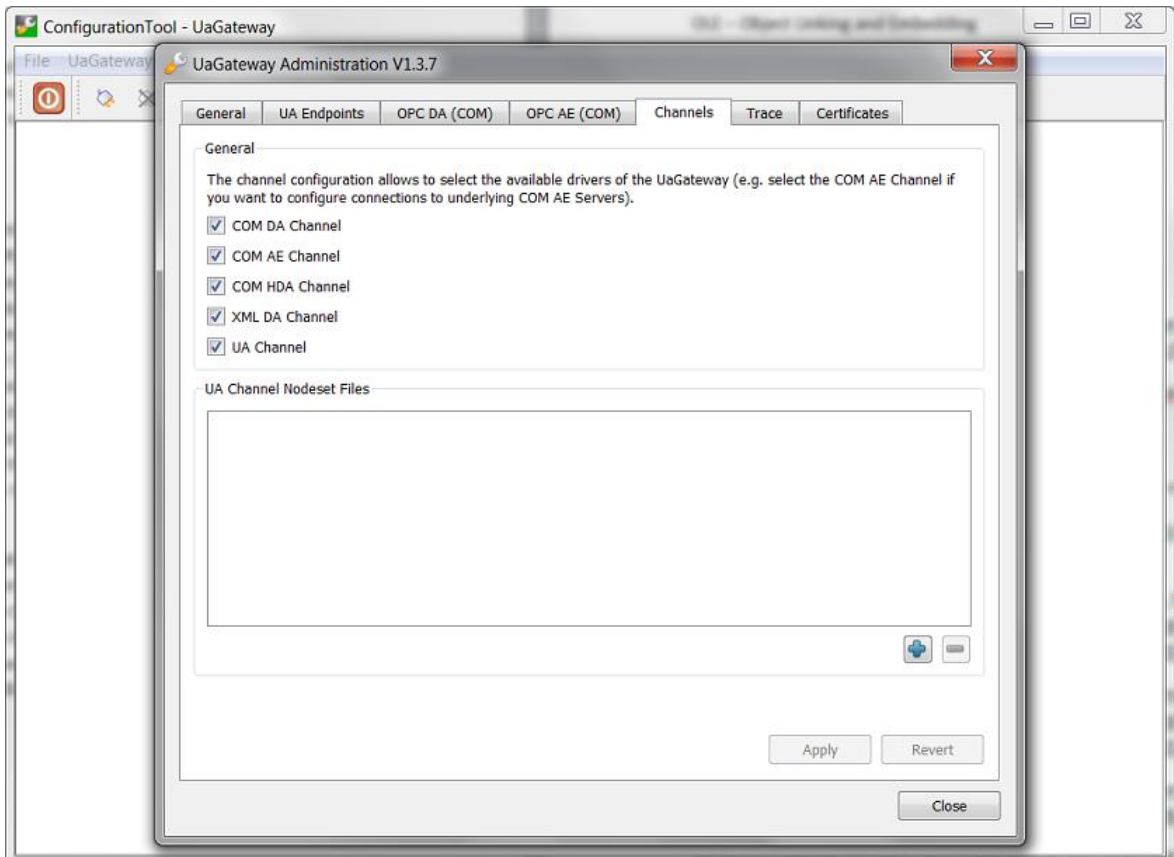


Figure 22 - Unified Automation UaGateway

5.2.2 Ensenso – Halcon communication

To create this communication is significantly less difficult. Halcon vision library installation includes native interface to camera drivers. Therefore is necessary only to install the Ensenso drivers and link to the camera. To match camera IP address you can use programme NxView which is delivered with the camera and which includes auto

configuration tool. Establishing of the software connection is matter of just few lines of code in Halcon.

5.2.3 Ensenso – Halcon – Kuka communication

Here are two concepts possible. The Ensenso N20 is communicating exclusively through Ethernet interface and communication to the Kuka is also realized with Ethernet. Therefore you can use a router to establish a communication knot for Ensenso – Halcon – Kuka communication. However because of all the obstacles I faced during realization of the OPC communication, I decided not to disturb functional Kuka – Halcon connection.

I decided to use external network card and establish the communication by this (much safer) parallel way. On following illustration you can see how the communication was eventually running.

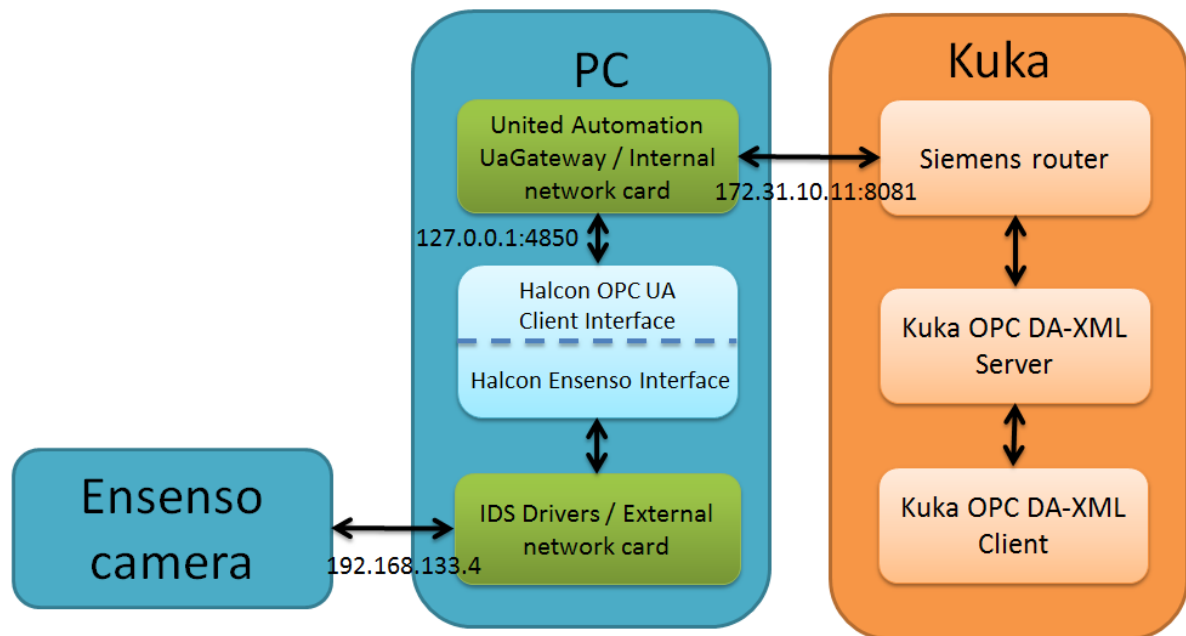


Figure 23 - Communication of the vision system

5.3 Camera setting

Setting of the camera can be done either through default camera drivers and program NxView or from Halcon. If the setting is changed manually from Halcon, every camera parameter requires being set individually on one line of code.

The NxView program has advantage of instant visualization of results and more user friendly interface. Setting is done by shifting of sliders and then saved into the camera in form of “.json” file. However the camera cannot store more than one setting at the same time, therefore if the camera is used for more than one task or is necessary to switch between camera setting, it is recommended to create more “.json” files in NxView

and use Halcon to load whole files instead of changing camera parameters one after another.

On the Figure 24 you can see 3D image from the camera. NxView is using pseudo-color to distinguish different Z-distance.

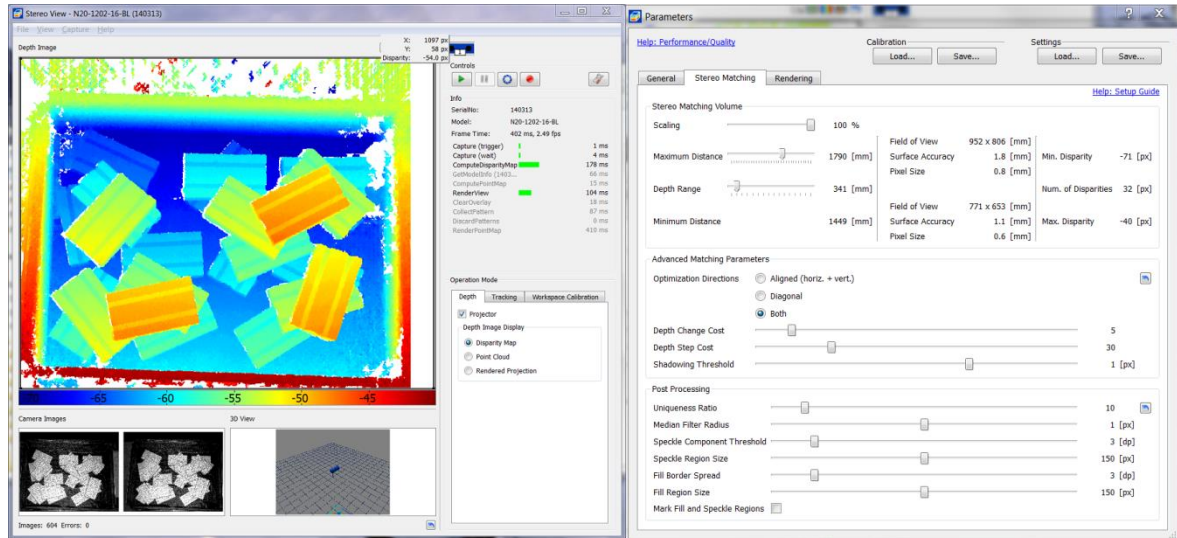


Figure 24 - NxView 3D camera setting

5.4 Camera calibration

There are two types of camera calibration necessary. We can call them internal and external. The internal calibration aims on compensation of lens distortion and creation of scale, it can be performed either from NxView or from Halcon and it is using the same calibration plate. I reached better results with calibration created through NxView.

External calibration (also called hand-eye calibration) is necessary due to establishing a relation between camera coordinate system and robot coordinate system. There are two configurations possible – stationary camera or robot mounted camera.

Like the camera calibration, the hand-eye calibration is based on providing multiple images of a known calibration object. But in contrast to the camera calibration, here, the calibration object is not moved manually. Either it is moved by the robot in front of a stationary camera or the robot moves the camera over a stationary calibration object. The pose, i.e., the position and orientation, of the robot tool in robot base coordinates for each calibration image must be known with high accuracy! [9]

This results in a chain of coordinate transformations (see figure 25). In this chain, two transformations (poses) are known: the pose of the robot tool in robot base coordinates $baseH_{tool}$ and the pose of the calibration object in camera coordinates $camH_{cal}$, which is determined from the calibration images. The hand-eye calibration then estimates the other two poses, i.e., the relation between the robot and the camera and between the robot and the calibration object, respectively. Note that the chain consists of different poses depending on the used scenario. [9]

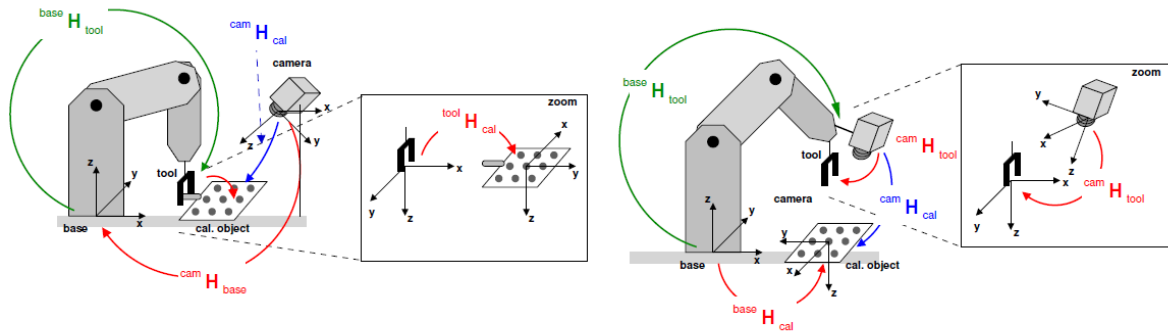


Figure 25 - Chain of transformations [9]

Practically is hand-eye calibration performed so that you save position of the robot in robot coordinate system with every snapped image. Halcon supports several kind of robot transformations but essential is to save the coordinates in correct order (first X,Y,Z translation and then X,Y,Z rotation)

For successful and accurate calibration is also necessary to take images of calibration plate with large orientation differences and on whole field of view of the camera. I was working with robot TCP accuracy of 0,35 mm and I reached average hand-eye calibration error 1,64 mm and 0,4°. Also we must consider physical camera accuracy of 0,85 mm in X and Y and 2,1 mm in Z. Sum of all these accuracies is 2,84 mm in X and Y axis and this is also theoretical maximum accuracy of the vision system in this task. Practical result is always worse because of not perfect recognition of the workpieces.

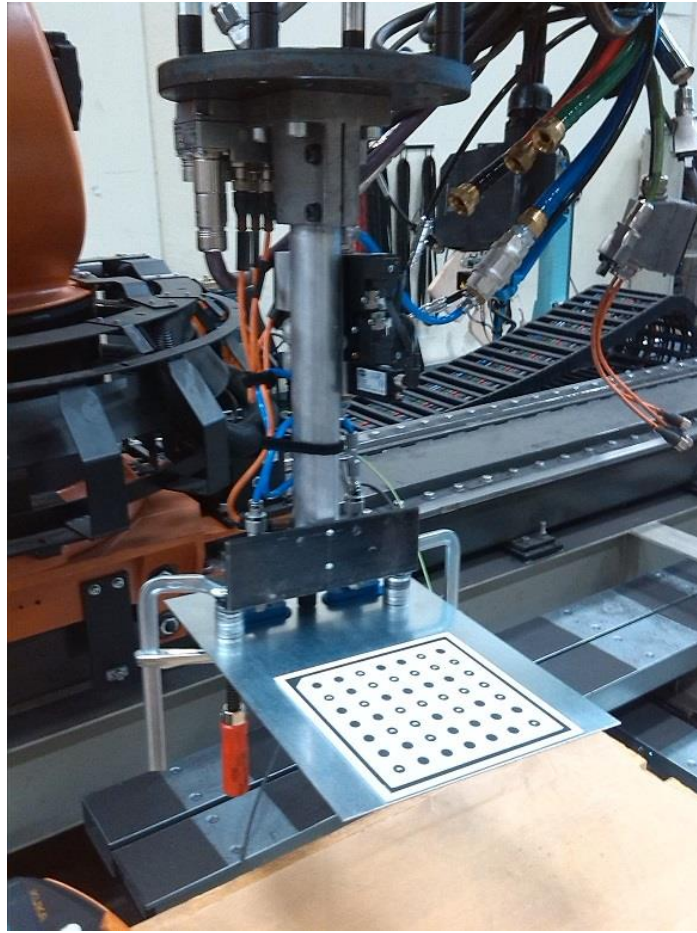


Figure 26 - Performing of hand-eye calibration

5.5 3D Image recognition

For the recognition of workpieces I used their CAD models. During the solution it turned out that the distance of 2000 mm is too far for robust results so in order to increase accuracy I had to decrease the distance to ca. 1800 mm. This is a minimum distance in which camera field of view covers whole box with workpieces and also a limit of used camera stand. This reduction unfortunately did not take much of effect. Halcon constantly recognized artificial workpieces on wrong positions, no matter on search algorithm setting or CAD model changes. Eliminating of this failure was possible only by increasing a threshold for match with CAD model, but that caused situation where workpieces were not found at all.

Cause for this situation can be a relatively small size of workpiece in context of whole field of view and also simplicity of the workpiece's surface. It is a paradox but for 3D image recognition is more suitable to have a workpiece with complicated shape because it can be more clearly and unambiguously fitted into 3D point cloud. Results with sufficient accuracy were reached with reading distance of ca. 700 mm, but used 3D image from this distance was capturing only ca. one third of the box. Therefore it would be necessary to reconstruct the robotic cell and attach the camera on the robot. After a

consultation with IDS and FLT it was decided to finish the task as 2,5D vision solution with Ensenso camera working in 2D mode with shape-based matching technique. On following picture is point map delivered from the camera and Z-distance image with recognized workpieces from ca. 700 mm reading distance.

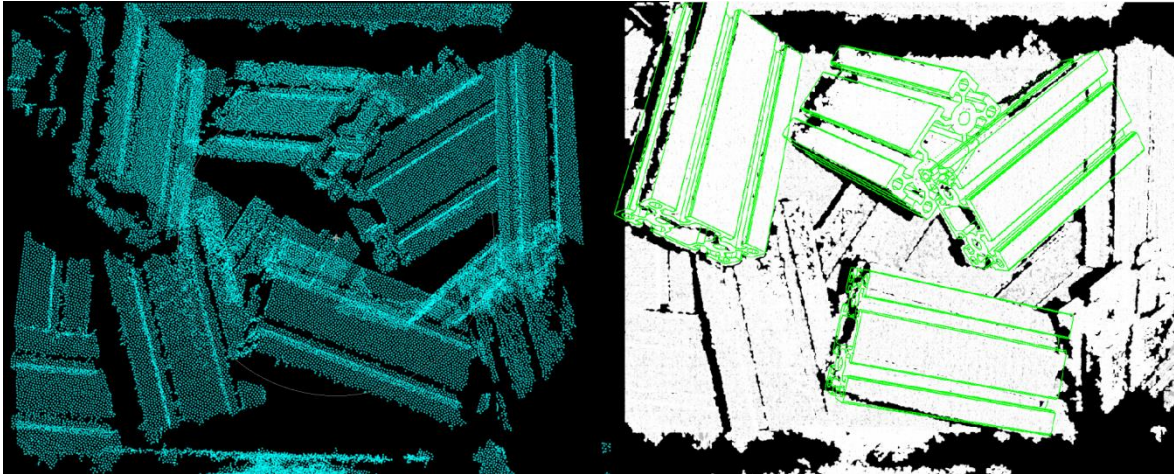


Figure 27 - 3D Image recognition

5.6 2,5D Image recognition

Ensenso camera allows the user to work with 2D image from left or right camera and you also can choose if you want raw image (which you must rectify in Halcon) or directly image rectified by internal Ensenso calibration. I was using implicitly rectified image from the left camera. Used hand-eye calibration was the same as in previous 3D image recognition attempts, because the camera stayed on the same position.

5.6.1 Simplified task

Theoretically Halcon could still do full bin picking solution, because it can estimate all 6 degrees of freedom of a workpiece just from a 2D image (see chapter 2.1). However my task was not the case. It was because the camera was operating from very large distance and Halcon could not precisely estimate X and Y rotations of the workpieces. Reached tolerance in X and Y angles was $\pm 15^\circ$ therefore we had to simplify the task on 2,5D bin picking, where the workpieces were pre-oriented and stacked in layers, camera system then had to recognize only X,Y,Z position and Z rotation.



Figure 28 - Box with workpieces

5.6.2 Pattern recognition

With this task Halcon robustly recognized position of the workpieces. Program was running on notebook with quad-core Intel i7 processor with nVidia Quadro K3100M graphical card and 8 GB of RAM. Computing time necessary for image recognition was from 3 to 6 seconds. It differs according to amount of workpieces left inside the box.

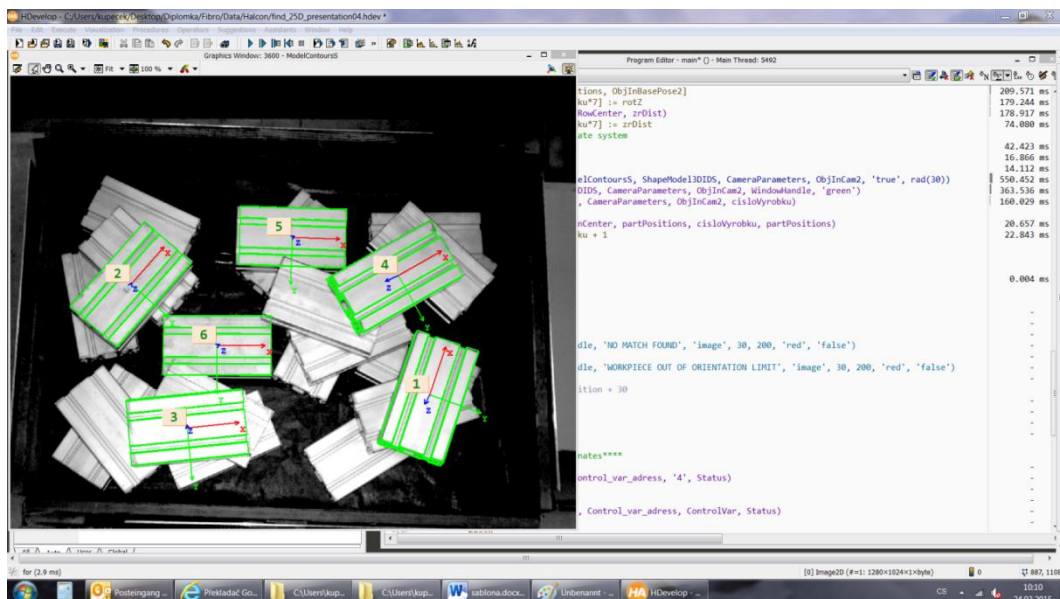


Figure 29 - Detected workpieces

With this simplified task Halcon could robustly recognize X,Y position and Z rotation, however the position in Z which was achieved just from 2D image was not accurate enough. Therefore I had to combine 2D and 3D vision and I got the correct Z - position from the 3D image. Program detected workpiece in 2D image and saved selected coordinates. Then it used pixel position of the workpiece's center and go into 3D image for the Z distance. To avoid potential blind spot in the 3D image, the programme computes average value from 3 pixel neighborhood of the workpiece's center.

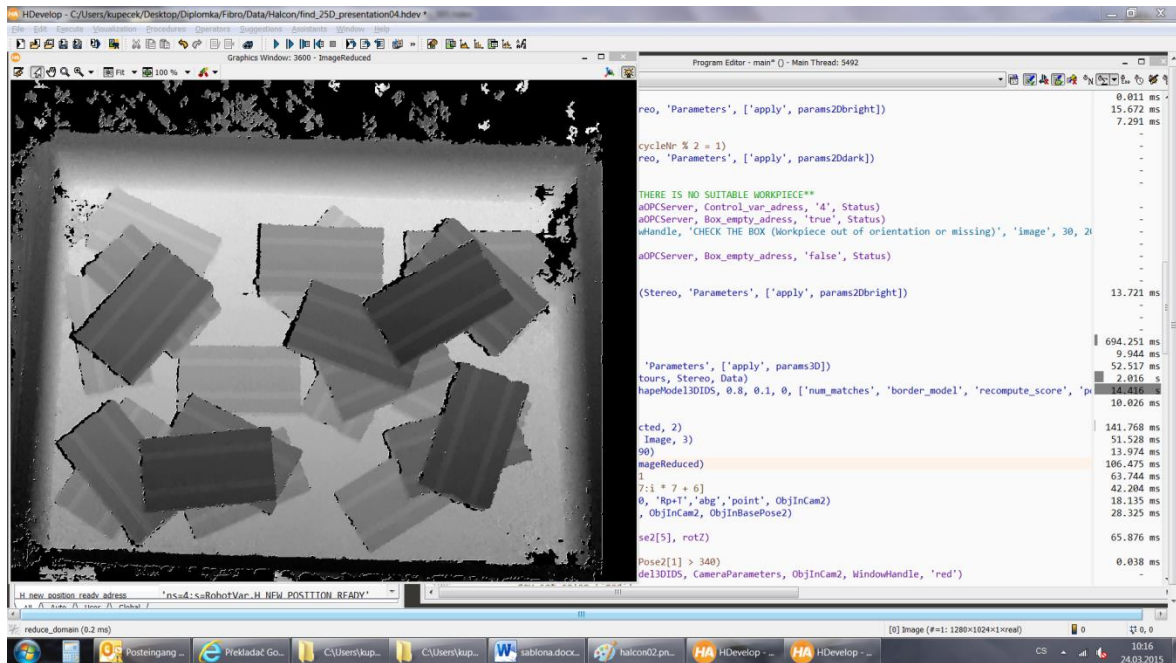


Figure 30 - Image of Z distance

Example of Halcon programme:

```
grab_image(Image2D, Stereo)
dev_update_window('off')
set_framegrabber_param(Stereo, 'Parameters', ['apply',
params3D])
grab_data(Image3D, Region, Contours, Stereo, Data)
    find_shape_model_3d(Image2D, ShapeModel3DIDS, 0.8, 0.1,
0, ['num_matches', 'border_model', 'recompute_score',
'pose_refinement', 'max_overlap'], [14, 'true', 'true',
'least_squares_very_high', 0.05], ModPoseS,
ModPoseErrS, ScoreS)
dev_update_window('on')
*Model found*
for i := 0 to |ScoreS| - 1 by 1
ObjInCam0 := ModPoseS[i * 7:i * 7 + 6]
convert_pose_type(ObjInCam0, 'Rp+T', 'abg', 'point', ObjInCam2)
```

5.6.3 Lighting conditions

The robotic cell was not exposed to direct sunlight and the Ensenso camera is using integrated LED light when capturing new 2D image or a pattern projector for 3D image. After testing with different lighting conditions inside the production hall the integrated LED light and pattern projector turned out to be robust against changes of the ambient lighting conditions.

However two lighting obstacles occurred during the testing. When the workpieces were directly under the camera (perpendicularly to the lighting) reflexion from the shiny surface causes high inaccuracy in Z distance and bad pattern recognition of parts. On the other hand, when workpieces were thronged to the far bottom corners, they were not recognized because of lack of light and contrast. These two obstacles occurred in ca. 5% of cases.

I solved this situation by dynamic changes in lighting setting of the camera. When no workpiece was recognized the camera switched from standard setting to bright (longer exposition time and LED light pulse) and took new picture. Halcon then tried to find workpiece on this new image. When no match was found, the camera switched to dark lighting setting (shorter exposition time and LED light pulse) and Halcon tried again. This schedule STANDARD – BRIGHT – DARK was repeated twice and if no match was found the box was declared as empty.

5.7 Mode selection

User can choose between manual and automatic mode. This selection is done on Kuka SmartPad and Halcon vision library is used to show current progress of image processing.

5.7.1 Manual mode

This mode allows user to choose which workpiece to pick. Halcon vision library recognizes workpieces in the box and to every suitable assign a number. Operator then picks a number on the PC screen and press corresponding button on Kuka SmartPad. Halcon then sends coordinates to Kuka robot, the robot goes for selected workpiece and the cycle starts again.

Suitable workpiece to pick is such workpiece where is no risk of collision of the robot to the camera stand. Operator remains with responsibility to pick a workpiece with no obstacle above gripping position.

5.7.1.1 Filter of results

To avoid potential collision to the camera stand Halcon filters results. When a workpiece below a certain line is found (in bottom half of image) its orientation is investigated. If the orientation of the workpiece requires such orientation of robot gripper which would cause collision, this workpiece is considered as not suitable. Position of the border line together with orientation limits of the workpieces in the box were determined by testing.

5.7.2 Automatic mode

If operator select automatic mode the vision programme runs in loop and does not require any intervention. It stops when whole box is empty and then the robot goes back the basic position. Major change is extended filtering which also identify the best workpiece to pick.

5.7.2.1 Filter of results

Initial filtering is the same as in manual mode. When all workpieces in orientation limits are found, they are compared by their height in the box. The workpiece which is on the top is then declared as the best and Halcon sends its coordinates to Kuka robot which picks it.

5.8 Robot programme

Robot type Kuka KR 360-3 was connected with KRC4 controller and robot programming was done directly through Kuka SmartPad.

After initialization the robot goes to its basic position and asks operator to select a mode. Then it performs a cycle i.e. in manual mode it pick and place one workpiece from the box on a table, in automatic mode it empty whole box and goes back to basic position. Speed of the robot movement is reduced due to danger of slipping of the workpieces from vacuum cups. Also is determined upper limit for robot movement due to risk of collision with the camera.

During tests I had to change vacuum cups and use smaller ones because of better gripping tolerance, however these new vacuum cups had different screws and required adapters. The adapters were unfortunately so long that the proximity switch was out of its working distance and become unusable. Therefore the contact with workpiece had to be detected by a vacuum sensor. Kuka uses interrupt routine which turns on the vacuum pump and slowly goes to gripping position, when the vacuum is reached the interrupt routine stops the robot movement.

5.8.1 Synchronisation with Halcon

Kuka and Halcon are communicating via shared variables in OPC server. On several places in Kuka and Halcon programs are synchronization subroutines which supervise correct program flow during whole execution. This synchronization is done by a dedicated OPC value which is sequentially iterated and reset either by Kuka or Halcon. It is located among others on the beginning and the end of a subroutine which sends coordinates. During this crucial communication are displayed diagnostic messages on the monitor to allow the operator visual control that system is running correctly.

Example from Kuka program:

```
PTP basic Vel=30 % PDAT27 Tool[11]:vacuum_middle Base[11]:test2d

auto_man_mode ()
syncro()
WAIT FOR CONTROL_VARIABLE==4
get_halcon_pos_vector_t1()

loop

PTP toppickingpoint CONT Vel=30 % PDAT25 Tool[11]:vacuum_middle
Base[11]:test2d
PTP prepickingpoint CONT Vel=15 % PDAT17 Tool[11]:vacuum_middle
Base[11]:test2d

search()
interrupt off
$advance=3
WAIT FOR ( IN 3393 ';;;;;;;;;' )

PTP toppickingpoint CONT Vel=15 % PDAT26 Tool[11]:vacuum_middle
Base[11]:test2d
PTP preplacepoint CONT Vel=30 % PDAT19 Tool[11]:vacuum_middle
Base[11]:test2d

syncro()

PTP placepoint CONT Vel=30 % PDAT20 Tool[11]:vacuum_middle
Base[11]:test2d
```

5.9 Risk analysis

During the testing I did not face all conditions which could result in a dangerous situation therefore I don't have all practical experiences. However following potential hazards could be simulated or tested.

5.9.1 Dirty camera lens

If the lens gets dirty due to dust or dirt in the air then the image processing will most likely identify workpieces with lower accuracy or not detect them at all. Due to lower accuracy some of them couldn't be sucked to the vacuum cups because the gripping position would not avoid the gap on workpiece's surface. However the search pattern is set to 80% match with CAD model and therefore it shouldn't recognize any artificial workpieces and avoid collisions.

5.9.2 Broken lighting

If the LED light would broke down then whole vision programme would be dependent on current ambient lighting conditions. In the best scenario when the lighting would be intensive, the vision program would be operating in normal or bright mode and locate major part of the workpieces. However according to my testing I think that workpieces in far bottom corners wouldn't be identified due to lack of light.

In the worst scenario the image would be too dark for any image analysis and the robot will therefore go back to its basic position.

5.9.3 Broken pattern projector

Here I was able to do a test because the Ensenso camera allows the user to turn the pattern projector off. The image without a pattern projector was far too inaccurate on most of the field of view. Any further work with such system would be impossible and the robot would most likely collide into a workpiece due to inaccurate Z – distance. Such scenario can be mitigated when collision protection in robot is set.

5.9.4 Connection failure

This situation was easy to test. When cable was disconnected Kuka and Halcon stopped on first synchronization subroutine. Only critical part for a potential failure is during sending of workpiece's coordinates, but this subroutine is secured by control synchronization on the beginning and on the end as well. Therefore nothing terrible can happen because the system will only stop and the operator has time to find cause of the problem and then restart whole system.

6 Code recognition

Part of my work was also focused on Data Matrix code recognition. Task here was to investigate possible Data Matrix readers for given reading conditions and find alternative for Sick Lector 620. This reader was used on a different task for part tracking.

6.1 Reading conditions

Given reading conditions:

- Size of the Data Matrix code: 14 x 14 mm
- Type of matrix: 16 x 16 segments
- Reading distance: 230 mm
- Communication with Profinet

6.2 Comparison of manufacturers

Data Matrix reading is already mastered technology and successful application is matter of suitable lighting (especially for reading of Direct Part Marks). I found many different manufacturers with readers suitable for the job and their list with comparison of abilities is in Appendix. What I find interesting on this comparison is range of prices which starts on 551 Euro and goes up to 2450 Euro (without native Profinet support, they are using convertors).

6.3 Halcon capability

Halcon vision library is not direct competition to simple Data Matrix readers. Basic runtime license with code identification libraries cost ca. 700 Euro, and then you also need PC to run the application, camera and lens. In my eyes it is possible to recommend Halcon on more difficult applications starting with inspection tasks and everything more complicated than that. Or on problematic tasks which requires special optics (e.g. long distance reading) or using of special cameras (e.g. thermo cameras), because Halcon can work with any kind of image.

I tested its capability to read Data Matrix code on a testing image (Figure 31) which I got from a colleague. Please keep in mind that the image was taken by common commercial camera, there is little blur and noise and also reflection in the middle. The

programming of Code reading application in Halcon is very simple and you can use many example programmes for inspiration and easy implementation. On picture below you can see original image on the left and minimum quality image which still allowed Data Matrix reading on the right.

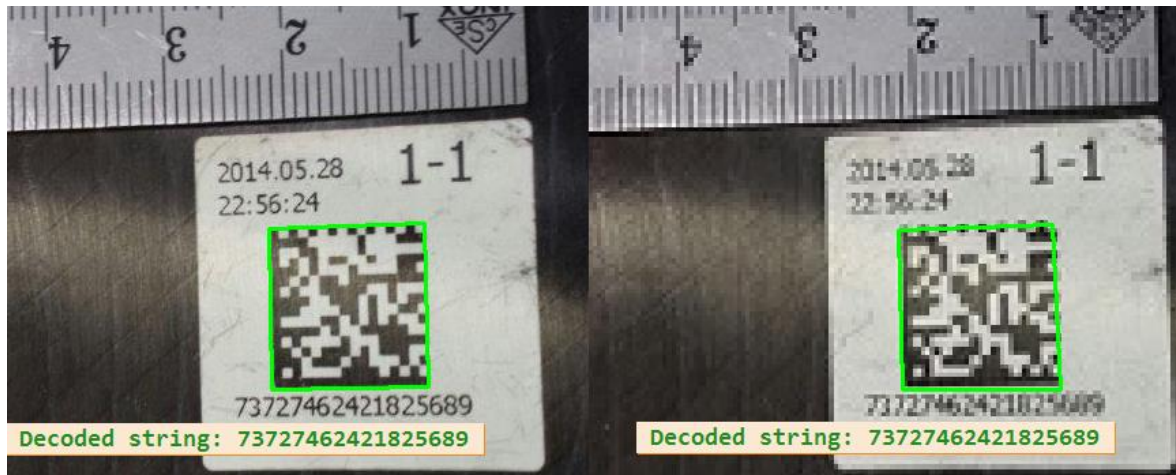


Figure 31 - Data Matrix codes

7 Conclusion

Bin picking is currently possible to realize by several techniques, but it is still expensive and difficult vision task. It requires advanced experiences with several 3D camera systems to determine their suitability and capability for the task in advance.

Vision system created by Ensenso 3D camera and Halcon vision library is suitable for given task, but not with nearly 2 m reading distance. If I decline creating of my own task-specific search algorithm (e.g. detect part in 2D and computation of 3D orientation in 3D point cloud from knowledge of the workpiece's geometry) it is necessary to significantly decrease the reading distance and scan just part of the box or to use bigger workpieces with more complicated shape. During tests with scanning of ca. 25% size of the box Halcon localized workpieces with sufficient accuracy. Such solution will decrease final cycle time but some optimization of the scanning cycle can be done, for example by periodical scanning of quarters in a clock-wise direction.

For beginnings with bin picking is better to use robot mounted camera instead of camera on stand, because the task can be easily simplified by reduction of reading distance or even the camera can be changed for more suitable type which come out from testing. Accuracy drop arising from dynamic camera configuration compared with avoiding of potential troubles can be neglected also because you are able to gain the accuracy back by lowering the reading distance.

During tests with Halcon as a Data Matrix reader turned out that limit for successful reading is approximately 2,3 pixels per a matrix segment. This is the same resolution as Cognex declares for their one-purpose Data Matrix readers as a limit. Therefore I am convinced that Halcon is truly robust and powerful tool for code recognition, but because of the price is not suitable for basic tasks.

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References

- [1] History. *Fibro Läßple Technology* [online]. [cit. 2015-01-07]. Available from: <http://www.fibro-laepple.de/en/company/geschichte.html>
- [2] WILSON, Andrew. Keystones of machine vision systems design. *Vision systems design* [online]. [cit. 2015-01-08]. Available from: <http://www.vision-systems.com/articles/print/volume-18/issue-8/features/keystones-of-machine-vision-systems-design.html>
- [3] Quick history of machine vision. *EPIC Systems blog* [online]. [cit. 2015-01-08]. Available from: <https://www.epicsysinc.com/blog/machine-vision-history>
- [4] IDS. *IDS Whitepaper 3D Stereo Vision* [online]. 2012 [cit. 2015-01-10]. Available from: <https://en.ids-imaging.com/whitepaper.html>
- [5] WILSON, Dave. Time-of-flight camera launched at VISION 2012. *Vision systems design* [online]. [cit. 2015-01-08]. Available from: <http://www.vision-systems.com/articles/2012/11/time-of-flight-camera-launched-at-vision-2012.html>
- [6] Infineon 3D Image sensor [online] . [cit. 2015-01-10]. Available from: <http://www.infineon.com/cms/en/product/channel.html?channel=5546d4614937379a0149382f21d6007a>
- [7] DEPTH CAMERA TECHNOLOGY COMPARISON AND PERFORMANCE EVALUATION. *Proceedings of the 1st International Conference on Pattern Recognition Applications and Methods* [online]. SciTePress - Science and Technology Publications, 2012-2-6, s. 438-444 [cit. 2015-01-10]. DOI: 10.5220/0003778304380444. Available from: <http://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0003778304380444>
- [8] Time-of-flight camera - An Introduction. *Theory of operation* [online]. 2014 [cit. 2015-01-10]. Available from: <http://www.ti.com/lit/wp/sloa190b/sloa190b.pdf>
- [9] MVTEC. *Solution guide III-C - 3D Vision* [online]. 2014 [cit. 2015-01-10]. Available from: <http://www.halcon.de/halcon/download/documentation/pdf-12/halcon-12.0-solution-guide-iii-c-3d-vision.pdf>
- [10] MVTEC. *HDevelop User's guide* [online]. 2014 [cit. 2015-01-10]. Available from: <http://www.halcon.com/halcon/download/documentation/users-guide-12/hdevelop/>
- [11] Fibro Läßple Technology erfolgreich gestartet. *Blechnet* [online]. [cit. 2015-01-07]. Available from: <http://www.blechnet.com/index.cfm?pid=11220&pk=394308&type=article&fk=325024>
- [12] Visualization of pose in Halcon example program. In: *Locate_car_door.hdev* [Halcon vision library]. [cit. 2015-01-09].
- [13] Visualization of pose in Halcon example program. In: *Create_shape_model_3d_lowest_model_level.hdev* [Halcon vision library]. [cit. 2015-01-09].
- [14] IDS. *IDS Whitepaper 3D Stereo Vision* [online]. 2012 [cit. 2015-01-10]. Available from: <https://en.ids-imaging.com/whitepaper.html>

- [15] FOIGT, Reiner. Stereo vision for high resolution 3D imaging. *Stereo vision - without projection* [online]. [cit. 2015-01-10]. Available from: http://ibv.vdma.org/documents/256550/5908105/2014-11-06_1_1100_Ensenso.pdf/e6767640-fcc9-4347-b761-fca20a42658d
- [16] FOIGT, Reiner. Stereo vision for high resolution 3D imaging. *Stereo vision - with projection* [online]. [cit. 2015-01-10]. Available from: http://ibv.vdma.org/documents/256550/5908105/2014-11-06_1_1100_Ensenso.pdf/e6767640-fcc9-4347-b761-fca20a42658d
- [17] Time-of-flight camera - An Introduction. *Theory of operation* [online]. 2014 [cit. 2015-01-10]. Available from: <http://www.ti.com/lit/wp/sloa190b/sloa190b.pdf>
- [18] DEPTH CAMERA TECHNOLOGY COMPARISON AND PERFORMANCE EVALUATION. *Proceedings of the 1st International Conference on Pattern Recognition Applications and Methods* [online]. SciTePress - Science and Technology Publications, 2012-2-6, s. 438-444 [cit. 2015-01-10]. DOI: 10.5220/0003778304380444. Available from: <http://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0003778304380444>
- [19] SICK. *Machine Vision Introduction*. Version 2.2. 2006, 56 p.
- [20] MVTEC. *Solution guide III-C - 3D Vision* [online]. 2014 [cit. 2015-01-10]. Available from: <http://www.halcon.de/halcon/download/documentation/pdf-12/halcon-12.0-solution-guide-iii-c-3d-vision.pdf>
- [21] Visualization of pose in Halcon example program. In: *Depth_from_focus.hdev* [Halcon vision library]. [cit. 2015-01-10].
- [22] KARPINSKY, Nikolaus a Song ZHANG. High-resolution, real-time 3D imaging with fringe analysis. *Journal of Real-Time Image Processing* [online]. 2010, vol. 7, issue 1, s. 55-66 [cit. 2015-02-27]. DOI: 10.1007/s11554-010-0167-4.
- [23] Roboterführungssysteme. In: *PLB-500* [online]. [cit. 2015-01-13]. Available from: <https://www.sick.com/de/de/systemloesungen/roboterfuehrungssysteme/plb/plb-500/p/p294546>
- [24] Roboticky vyber objektu z bedny - Bin picking. In: *Reseni vyberu po castech* [online]. [cit. 2015-01-13]. Available from: http://infocube.cz/wp-content/uploads/2013/08/obr-2_small.png
- [25] Industrial Robotics. In: *Pleora technologies - Applications* [online]. [cit. 2015-01-13]. Dostupné z: <http://www.pleora.com/applications/industrial-robotics>
- [26] 3D-Bildverarbeitung aus dem Baukasten. *Sensor-Baukasten für die 3D-Bildverarbeitung* [online]. [cit. 2015-04-13]. Available from: http://www.elektroniknet.de/automation/sonstiges/?_aid=89631&gid=3201&cp=5
- [27] N20 Stereo 3D Camera 600. *IDS Web pages* [online]. [cit. 2015-04-13]. Available from: <https://en.ids-imaging.com/store/n20-stereo-3d-camera-600.html>
- [28] 3D Vision. SICK. *Sick* [online]. [cit. 2015-01-14]. Available from: http://www.sick.com/group/en/home/products/product_portfolio/vision/pages/high-end_cameras.aspx

- [29] MFD PINZE AD ESPANSIONE HANDLIG GIMATIC. GIMATIC. [online]. [cit. 2015-01-14]. Available from: <http://www.gimatic.cz/en/products/handling/pinze%20ad%20espansione/mfd>
- [30] Mini-Greifinger MF Automation GmbH. [online]. [cit. 2015-01-14]. Available from: <http://www.mf-automation.com/mini-greifinger/>

Data on CD

Application video

Photos from testing

Source code of Vision program

Source code of Robot program

PDF of Master thesis

Appendix 1 – Comparison of suitable Data Matrix readers 1/2

Table 5 - Data Matrix readers 1/4

Name	Sick Lector 620 Professional	Cognex	Keyence SR 750 series
Model	ICR620S-T11503 Professional	300 X + 10,3 lens	SR 752
Resolution [px]	752 x 480	800 x 600	752 x 480
Focal length [mm]	7	10,3	
Reading distance [mm]	40 - 1500	0 - 374	180 - 305
Reading frequency [Hz]	60	60	
Protection	IP 65	IP 65	IP 65
Interface	Ethernet, USB, CAN, Serial	Ethernet, Serial	Ethernet, Serial
Colour of lights	Blue, Red	Optional	Red
Dimensions [mm]	71 x 43 x 35,6	73 x 54 x 42	84,4 x 47 x 46,4
Operating Voltage [V]	10 - 30 DC	21,6 - 26,4 DC	21,6 - 26,4 DC
Price [Euro, no MwSt.]	2065 (1703 Fibro price)	2291 + ? (Angebot)	2525
Profinet	YES	YES	YES

Table 6 - Data Matrix readers 2/4

Name	Datalogic Matrix 300	Siemens MV420	Sensopart Visor V10
Model	Matrix 300 4x2 (9mm)	SIMATIC MV420 SR-P	V10-CR-S1-R12D
Resolution [px]	1280 x 1024	752 x 480	736 x 480
Focal length [mm]	9	16	12
Reading distance [mm]	25 - 315	10 - 400	40 - 680
Reading frequency [Hz]	60	70	25
Protection	IP 67	IP 67	IP 67
Interface	Ethernet, Serial	Ethernet	Ethernet, Serial
Colour of lights	Red / White / Multiple	Red / White	Red / White / IR
Dimensions [mm]	94 x 54 x 43	52,5 x 70,7 x 39,5	65 x 45 x 45
Operating Voltage [V]	10 - 30 DC	19,2 - 28,8 DC	18 - 26,4 DC
Price [Euro, no MwSt.]	1809 (Angebot)	2040 (Angebot bei tel.)	850 (Angebot)
Profinet	YES	YES	YES

Appendix 2 – Comparison of suitable Data Matrix readers 2/2

Table 7 - Data Matrix readers 3/4

Name	Leunze electronic	Ioss	Microscan Mini Hawk Xi
Model	LSIS 222 M5M-R1	DRM220	FIS-6310-1210G
Resolution [px]	844 x 640	752 x 480	1280 x 1024
Focal length [mm]			
Reading distance [mm]	50 - 330	10 - 500	25 - 254
Reading frequency [Hz]	4		
Protection	IP 65	IP 67	IP 54
Interface	Serial	Ethernet, Serial,	Ethernet, Serial
Colour of lights	Red		Red
Dimensions [mm]	40 x 32 x 47	85 x 52 x 42,5	25,4 x 45,7 x 53,3
Operating Voltage [V]	10 - 30 DC	24 DC	10 - 30 DC
Price [Euro, no MwSt.]	551 + 536 convertor (Angebot)	2450 + 635 convertor (Angebot)	1858 (no convertor)
Profinet	NO PROFINET	NO PROFINET	NO PROFINET

Table 8 - Data Matrix readers 4/4

Name	Omron FQ-CR
Model	FQ-CR20100N-M
Resolution [px]	752 x 480
Focal length [mm]	
Reading distance [mm]	32 - 380
Reading frequency [Hz]	
Protection	IP 67
Interface	Ethernet
Colour of lights	White
Dimensions [mm]	108 x 46 x 49
Operating Voltage [V]	21,6 - 26,4 DC
Price [Euro, no MwSt.]	1829 (no convertor)
Profinet	NO PROFINET