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Machine vision in motion guidance

Thesis

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Thesis Abstract

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Cognex Micro-series is a compact machine vision, which can be used in various tasks. The purpose of this work is to try the object identification features of the machine vision system in practice and to implement a communication method between the vision system and the logic controller.

This project studies machine vision, PROFINET industrial ethernet and Beckhoff TwinCAT automation software. This project is focused in machine vision systems from perspective of object location and motion guidance.

Keywords: Machine vision, smartcam, PROFINET, twincat, softPLC

SEINÄJOEN AMMATTIKORKEAKOULU

Opinnäytetyön tiivistelmä

Koulutusyksikkö: Tekniikan ala

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Cognex Micro-sarjan älykamerat ovat pienikokoisia konenäkölaitteita, joita voidaan käyttää monissa eri tehtävissä. Työn tarkoituksena on testata älykameraa käytännön kappaleen tunnistuksessa ja paikoituksessa, sekä päättää paras tiedonsiirtotapa, jolla kameralaite saadan kytkettyä logiikkaohjaimeen.

Tässä työssä on tutustuttu konenäkölaitteisiin, PROFINET-tiedonsiirtoon ja Beckhoffin TwinCAT-ohjelmistoon. Työssä perehdytään konenäköön ja älykameroihin erityisesti kappaleenpaikoituksen ja liikkeenohjauksen kannalta.

Keywords: konenäkö, älykamera, PROFINET, TwinCAT

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Terms and abbreviations

Real-time In computer science real-time means that the system must respond in a defined period of time. If processing takes too long, the result is worthless. By contrast, non-real-time system works without these time limitations.

Smartcam Small sized machine vision system with an integrated vision processing and communications

1. INTRODUCTION

1.1 Background

Machine vision systems are becoming more common in automation industry, because of their constantly increasing performance and more affordable price. Seinäjoki University of Applied Sciences has recently acquired an Cognex machine vision device. Project related to this device was offered. Author decided to accept the project because of his interest in digital photography and the topic fits well into his studies in automation technology.

This project studies usage of machine vision systems in motion guidance. Work covers components of machine vision systems and studies Beckhoff TwinCAT automation software and PROFINET industrial ethernet.

1.2 Objectives

Goal of this project was to try out machine vision in real-like environment. Project included building means of communication between the Cognex machine vision system and the Beckhoff TwinCAT automation software. Purpose of this project was to build vision based system, which can pick up an object that is placed on a working surface and move it to drop location. Machine vision was used to locate the object, and TwinCAT to control movements.

1.3 Structure

Chapter 2 introduces the concept of machine vision, it's history and the benefits it can bring to automation industry.

Chapter 3 introduces the key components, which every machine vision system needs to operate. This key components include lighting, optics, sensor and communications.

Chapter 4 studies PC as an automation controller. This chapter is mainly focused on Beckhoff TwinCAT3 automation software.

Chapter 5 covers the industrial ethernet solutions. The main focus is on PROFINET, because it was used in this project.

Chapter 6 explains how the project was implemented in practice and how different components were connected together.

Chapter 7 examines the achieved results and draws conclusions.

2. MACHINE VISION

Machine vision is a digital system which gathers information about surrounding world in form of images. Machine vision system, includes components for fetching an image, image processing and communications to send the results for automation system. Machine vision is used for inspection, identifying, counting and robot guidance in automatic systems. Despite the high level of automation in production environments, inspection is often done by humans. Machine vision allows the automation of such tasks. (Pikkarinen 2004)

Machine vision systems are used in the industry since they lack the weaknesses of human workers. Machine vision does not get tired or sick and it is faster and more accurate than human worker. Machine vision can be installed in environments, which are too dangerous or hazardous for humans. Machine vision systems are suitable for tiresome, repetitious tasks and tasks with a quick cycle time. (Ahlroth 2010)

There are many prerequisites for using machine vision systems. Cost efficiency is often a major factor. The goal may also be to improve the quality of end products by using automated quality inspection or to improve the working conditions of human workers by replacing manual inspection with machine vision. (Pikkarinen 2004)

2.1. History of machine vision

Machine vision is a relatively new thing in automation. The concept of machine vision systems dates back to as far as the 1930's. The early applications used photo-multiplier detectors to sort food items. However, it took several decades for machine vision systems to evolve to the state we know it today. The invention of a CCD sensor in 1969 was a major break-through and made it possible to capture images digitally. The potential of machine based vision was noticed early, but the lack of computing power placed obstacles for implementing the vision systems. The first simple vision systems were introduced in the late 1980's. The image processing of vision systems requires high amount of processing power, which, at that time was not available, or needed expensive special components. In the 1990's the rapid improvement of computer technology made machine vision systems more practical, and they started to be more common on factory floor. (Wilson 2014) (Kuivanen 1999)

Traditional machine vision systems are based on PC-computers. This is due to the high calculation power needed for image processing. In the recent years camera products with integrated image processing capabilities have been introduced to the market. These products with an integrated image processor are called *smart cams*. Smart cams are standalone machine vision systems usually equipped with fieldbus or ethernet interfaces for the communication with other components of the automation system. Smart cam is a cost efficient and compact solution for machine vision system. (Sick AG 2006) (Ahlroth 2010)

2.2. Machine vision in robot guidance

When a robot is controlled by machine vision, the system is called visual servo control or visual servoing. This means giving eyes to otherwise blind robots. A camera may be fixed in the work space and observe the movement of the robot from a stationary position, or mounted to a robot manipulator, in which case the camera moves with the robot. (Chaumette & al. 2006) Visual servo control relies on machine vision, image processing and robot controller. New kind of flexibility can be achieved by a visual servo control. It can be used to automate tasks, which are impossible to automate in traditional ways. (Pikkarinen 2004)

Machine vision is needed in robotic applications, when traditional sensor systems are not sufficient. Generally there are three reasons for using machine vision in robot guidance.

- Determining the location and orientation of an object
- identifying an object by shape, size, color or other identifier such as text or barcode
- measuring an object to create or modify a robot program.

(Kuivanen 1999)

3. COMPONENTS OF A MACHINE VISION SYSTEM

Every machine vision system has few key components which are all required for the system to function. These key components are illumination, optics, sensor, image processing and communications. Introduction to those components is given in this section.

3.1. Illumination

All cameras operate by capturing light. Light is emitted by the lighting source and reflected by object and finally captured by camera. Lighting is therefore very important for successful image capturing process. Illumination is the way how the object is lid up. Lighting means the lamp that is generating the light. (Sick AG, 2006) In machine vision systems good illumination maximizes the contrast of the wanted features, minimizes noise and assures high repeatability in image quality. Sometimes feature of the interest is the outline of the object. Sometimes seeing details of the surface texture is needed. These requirements are somewhat contradictory and require different lighting setup for the best results. Image post processing done by software can be useful when highlighting faint features.. (Sick AG 2006)

A majority of lighting setups is based on light emitting diodes (leds). Leds are stable and predictable lighting sources and have very long life expectancy. Leds also have low power consumption. Another advantage of leds is that they can withstand high g-loads without failing. This means they can be mounted directly to vibrating or fast moving machines. Leds can also be switched on and off very quickly. This makes them excellent flash and strobe lights. (Microscan Systems) (Sick AG 2006)

3.1.1. Types of reflection

When a light ray hits a surface of an object, it may be absorbed or reflected in different ways. Understanding the behavior of light is helpful when lighting of machine vision system is being designed.

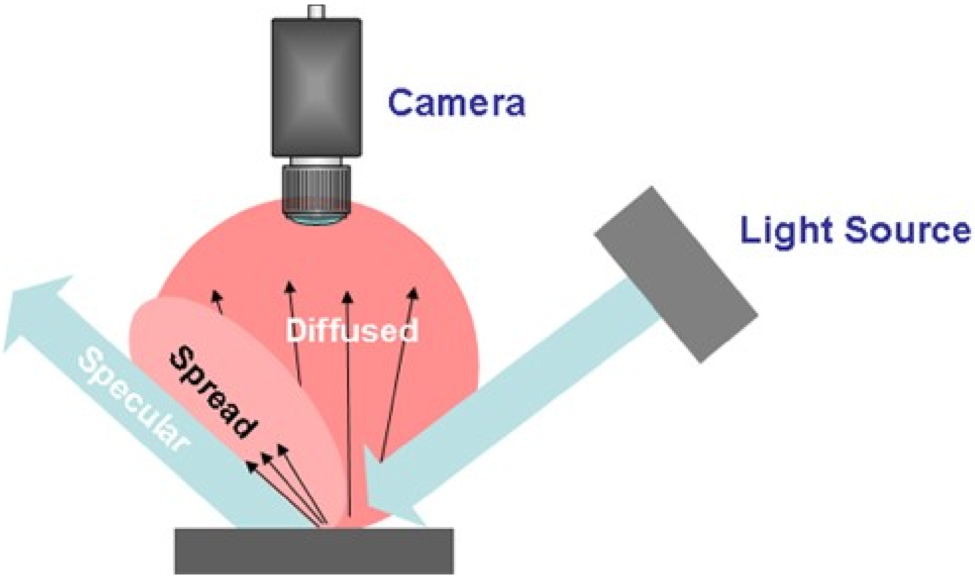


Figure 1: Reflection of light (Microscan Systems 2014)

Figure 1 shows different light reflections. Specular reflection happens when object reflects light directly. The angle of reflection is equal to the angle of incidence. A specular reflection occurs if the object has a smooth, mirror-like surface. Rough surfaces scatter light in all directions. This kind of reflection is called a *diffused reflection*. A diffused reflections can be used to investigate surface quality of the object. A s*pread reflection* has the properties of both specular and diffused reflection. Although the reflected light has the same major angle of reflection as incident light, it scatters in some degree. (Microscan Systems 2014) (Sick AG 2006)

3.1.2. Bright field / dark field illumination

Lighting can be divided into bright field lighting and dark field lighting depending on the angle between the optical axis of the camera and the lighting source. If the angle is small enough for specularly reflected light to reach the lens of the camera, the setup is considered as bright field lighting. If the angle is large enough, specular reflections cannot reach lens at all. This setup is considered as dark-field lighting. A smooth object reflects the light specularly away from the camera and in theory, the camera does not see anything. Figure 2 shows the paths of light rays in different setups. Dark field lighting is useful when a machine vision system is used to inspect deviations in the surface quality of the object. All anomalies, such as scratches scatter the light and make them appear bright for the camera. Dark field lighting can be used to find flaws, which are very difficult to find with any other method. (Sick AG 2006). (Microscan Systems 2014)

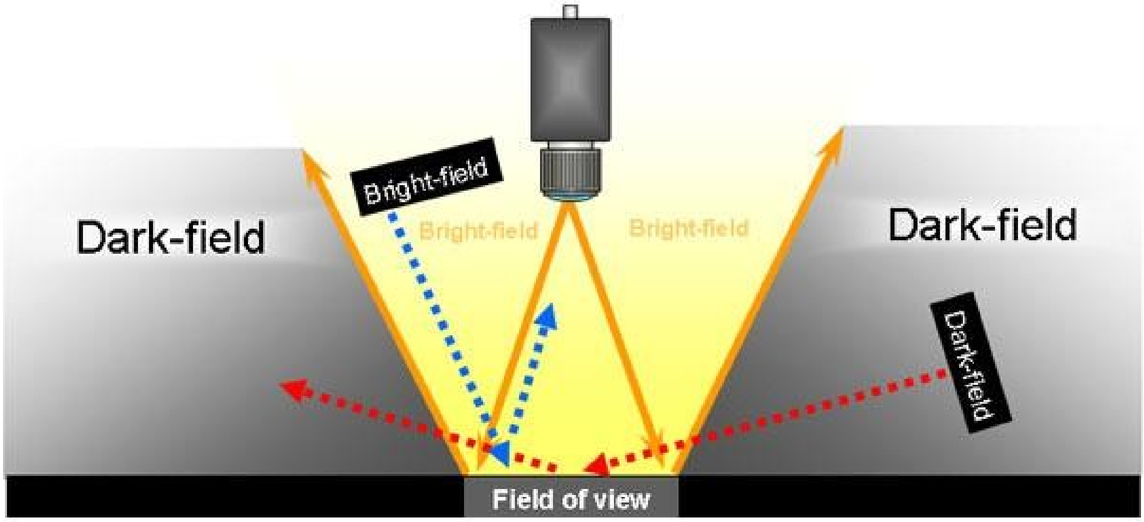


Figure 2: Dark-field and bright-field illumination (Microscan Systems 2014)

3.1.3. Lighting solutions

Directional lighting

Directional lights produce bright illumination and sharp shadows. Illumination is not particularly smooth over the object. Examples of direct lighting devices are spot lights and ring lights. Directional lighting is inexpensive, easy to install and sufficient for most machine vision installations. (Microscan systems 2014), (Halinen 2007)

Diffused lighting

The idea of the diffused lighting is, that light enters the object from all directions. This reduces shadows and makes reflective surfaces easier to manage. In the diffused lighting setups the light is reflected to object via other surface or trough light diffuser film. Dome lighting is one special application of diffused lighting. A sphere with a bright matte inside is placed over the object. The inside of the sphere is lid up. Figure 3 shows the design of dome light. This kind of lighting setup is used for difficult, highly specular objects. (Microscan systems 2014), (Halinen 2007)

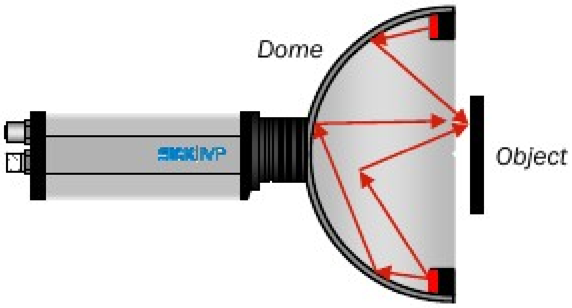


Figure 3: Dome lighting (Sick AG 2006)

Backlighting

In backlighting setups, lighting source is located behind the object. Therefore lighting source must be larger than the object Outside edges of the objects are clearly visible but the surface of the object can not be seen. Backlighting is useful when general shape of the object, such as dimensions are measured. (Halinen 2007)

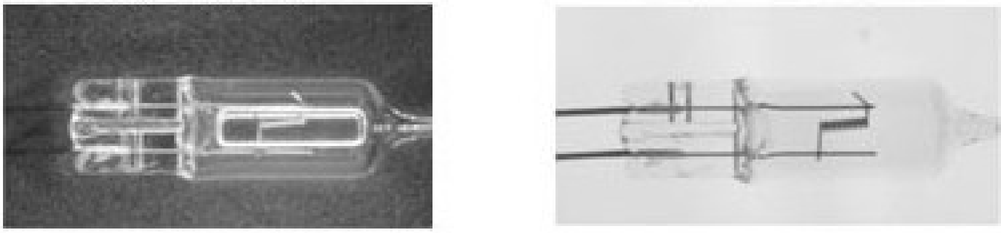


Figure 4: Backlighting (Microscan Systems 2014)

Figre 4 shows advantages of backlighting. Point of interest is the filament inside the bulb. The first picture is taken while using ring light. Filament can be seen, but not very clearly. Second image is taken using backlighting. Transparent bulb transmits most of the light straight trough, while filament and conductors inside the bulb are clearly visible. (Microscan systems 2014)

Flash and strobe lights

Flashes and strobe lights are used, when the examined object is moving at a high velocity. By using a quick flash of light, the movement of the object can be frozen. This prevents the image from blurring. (Halinen 2007)

3.2. Optics

In order to collect and focus light for the image sensor, some sort of lens system, or in other word, *objective* is needed. Objectives are actually very complex devices containing series of glass elements to focus the light to the sensor element of the camera. Objectives vary in their ability to collect light, and in their angle of view. In machine vision systems objective may be integrated to the sensor body, or be interchangeable. (Eismann & al. 2004) Sensor bodies with interchangeable lenses can be coupled with any lens fitting to the sensors *lens mount*. Interchangeable machine vision lenses usually do not have autofocus feature. Some of the most common lens mounts found in machine vision systems include C/CS mount, F-mount and M42 mount. (Ahlroth 2010)

3.2.1. Focal length

Focal length defines the angle of view of the lens. Terms focal length and angle of view are directly related and are basically different ways to express the same thing. Focal length of the lense is measured in millimeters. Focal length can be thought as a magnification of the lens, where longer focal length means more magnification. Objectives with short focal lengths have wide angle of view and are often called wide angle lenses. Objectives with long focal length have narrow field of view and are often referred as tele objectives. Besides objective, also size of the sensor element affects angle of the view of the camera. Smaller sensor size results narrower angle of view. For this reason same lens mounted to different cameras may result different angle of view. Prime lenses are objectives with fixed focal length. Zoom lenses have series of moving elements designed to provide variable focal length. Zoom lenses are generally less sharp than prime lenses due to compromises made in design. (Eismann & al. 2004)

3.2.2. F-Number and aperture

f-Stop or *f-number* defines the aperture size of the lens. Aperture is the opening, that controls how much light is passed trough the lens. This opening can be compared to the iris of an human eye. In camera technology aperture size is commonly given as an f-stop. F-stop indicates the aperture size as a fraction of focal length. Each f-stop resembles factor of two in amount of light collected. F-stop reported with lenses indicates the maximum opening of the aperture. For example lens with 35mm focal length and f/1.4 have maximum aperture of 35mm/1.4=25mm. Because f-number defines how much light is passed trough the lens, it also specifies shutter time needed for well exposed image. Therefore the f-number is sometimes referred as lens speed. Fast lens have small f-number. However, lens can be *stopped down* by using the setting ring found around the lens. Setting ring moves blades inside objective, which in turn open or close the aperture. Stopping down (increasing f-number) is often appropriate, because most lenses produce the best image quality when f-number around 10 is used.. (Eismann & al. 2004)

3.2.3. Depth of field

Depth of field is the distance between the closest and the farthest object which appear acceptably sharp in an image. Lenses can be focused only to one specific distance at a time. Subjects closer or further away are blurred. In practice, focusing is done by moving glass elements inside the lens. This can be done manually, by turning a setting ring on the lens, or automatically by the camera. Objects on all distances are certainly visible in the image, but further they are from the focus point, more strongly they are blurred. (Rinne 2008)

Depth of field is affected by several features of the camera. There is no easy formula for determining the depth of field, but it is important to keep in mind following things:

- The smaller the aperture (large f-stop), longer the depth of field
- Short working distance results short depth of field.
- Short focal lengths result long depth of field

(Rinne 2008)

Long depth of field can be archived, by using large f-number and short focal length.

3.2.4. Lens problems

Lens plays critical role in image quality. No lens is perfect, due to compromises in design and imprecision in manufacturing process. What is good enough lens, completely depends on application it is used on. If vision system is used to measure shapes and distances, high precision is required from the lens. (Halinen 2007)

Barrel Distortion

Barrel distortion makes the center of the image to bulge inwards. This is a common problem with wide angle lenses. Pincushion distortion is opposite of barrel distortion. The center of the image looks like it is pushed away. Pincushion distortion is mostly seen with long focal lengths. Figure 5 illustrates effects of barrel and pincushion distortions. Distortions can be corrected using an image pre-processing software. (Eismann & al. 2004)

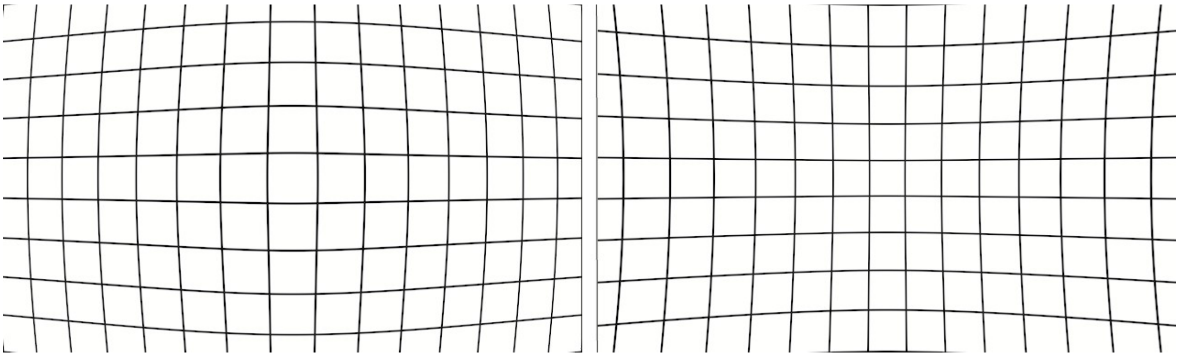


Figure 5: Barrel and pincushion distortions

Chromatic Aberration

Because glass elements of the lens have different refractive indexes for different wavelengths of the light not all of the light waves get focused into same point. Shorter wavelengths get refracted more than long wavelengths. This phenomenon of glass elements is called *dispersion* and result of it is chromatic aberration. Different colors of the image are out of alignment. (Rinne 2008) (Eismann & al. 2004)

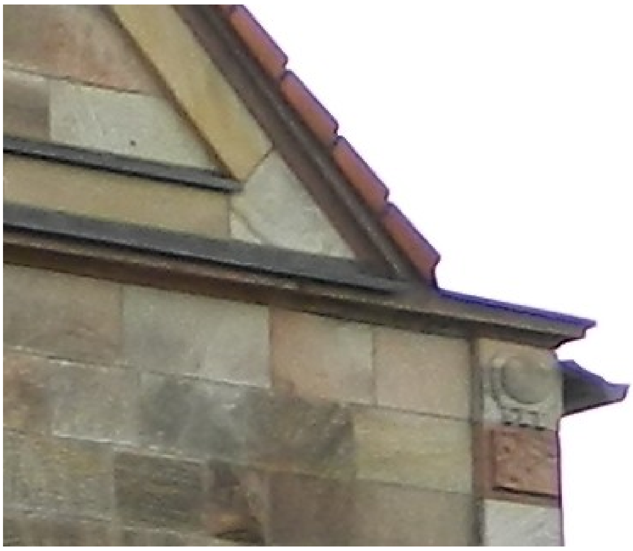


Figure 6: Chromatic aberration

Chromatic aberration causes purple fringing between high-contrast regions of the image. This can be seen in figure 6. High quality lenses are made of low dispersion glass to minimize chromatic aberration. (Eismann & al. 2004)

Sharpness

Sharpness is lenses ability to distinguish fine details. Sharpness is measured by the number of line pairs per millimeter the lens is able to resolve, while maintaining contrast between details. Some lenses have excellent sharpness in the center area of the picture, but sharpness significantly decrease at the corners. Sharpness can be examined by taking picture of lens test chart and inspecting the resulted image at 100% magnification. (Eismann & al. 2004)

3.3. Sensor

Sensor is the component, which converts light into electric information. Photosensitive picture elements, also called pixels are the smallest elements of an digital image. To form an image, pixels are arranged into a matrix. The amount of pixels in the matrix is resolution of the sensor. When light hits the photosensitive pixels, a charge proportional to the intensity of the light is produced. Typical resolutions for machine vision sensors are 640x480 (VGA), 1280x1024 (SXGA) and 1600x1200 (UXGA). (Sick AG 2006)

3.3.1. Sensor types

Most modern digital cameras use CCD or CMOS matrix sensors. Both of these sensor types are also commonly found in machine vision systems. CCD sensors have been more common due their better light sensitivity and better noise performance. However the performance of CMOS sensors have improved considerably in recent years, and they have started to become more common. CMOS sensors consume less power than CCD sensors and are more economical to produce. (Eismann & al. 2004)

3.3.2. Color filters

If sensor captures color images, each pixel is structured by three sub-pixels. Red green and blue. Because sensor elements of the digital camera are sensitive to all wavelength of the light, color filter is needed over the sensor. Each sub-pixel receives only designated wavelength of the light and colors can be separated. Each color is then converted to digital information of one byte or 8 bits, resulting total of 24-bit image. Best known filter pattern is so called bayer filter, which uses twice as many green pixels as blue and red pixels. Bayer filter pattern is shown in Figure 7. (Eismann & al. 2004)

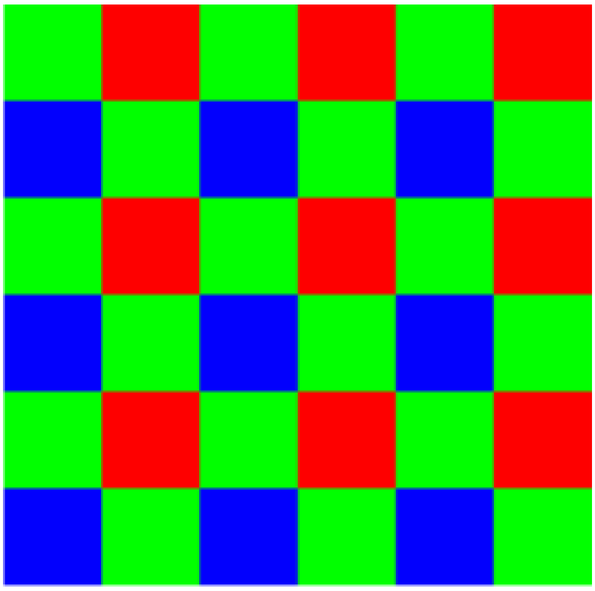


Figure 7: Bayer filter pattern

Most machine vision systems operate in grayscale, which means they can only differentiate 255 shades of gray. Grayscale cameras do not require color filters.

3.3.3. ISO sensitivity

ISO (International Standards Organization) defines the light sensitivity of an image sensor. Native sensitivity of digital sensors ranges from ISO 100 to ISO 400. Higher sensitivity makes the sensor more sensible to light and makes the sensor perform better in low-light situations. Sensitivity of an electronic sensor can be boosted higher by using electronic gain, but this also increases noise and decreases image quality. Increasing ISO sensitivity is usually the very last resort in low light situations. Using larger aperture, longer shutter time, or improved lighting is recommended. (Eismann & al. 2004)

3.3.4. Shutter and exposure

Human eye is capable of seeing wide range of dark and light shades, i.e. human eye has excellent dynamic range. Camera sensors however have much narrower dynamic range which means they have difficulties seeing details in light or dark areas of an image. Therefore amount of light entering the sensor must be controlled to fit the lighting situation. Shutter is a mechanism, which controls how long the sensor is exposed to light. In old film cameras the shutter was kept closed to prevent light from exposing the film. When picture was taken, shutter opened for defined time. Most digital cameras do not have mechanical shutter, but the principle is still the same. When the picture is taken, the sensor is electronically switched on, and after defined time, switched back off. (Eismann & al. 2004)

The time, where the sensor is collecting light is called exposure time. In machine vision system the shutter time is given in milliseconds. (Sick AG. 2006) Total *exposure is* affected by three matters. Shutter speed, aperture and sensitivity of the sensor. Because aperture and shutter speed can be set independently, same exposure can be archived with many different settings. Balanced exposure is important for finding details in the images. In overexposed images highlights will be completely white. In underexposed images shadows will be completely dark. In both cases image lacks detail. (Eismann & al. 2004), (Rinne 2008)

3.4. Image processing

Locating object from the image is usually the very first step for any machine vision application. In robot applications vision system reports reference coordinate of the object to the robot controller. Reference coordinate can be corner of the object or center of gravity point.

Digital filters / preprocessing

Coordinate Transformation is used to convert different coordinate systems, for example, image coordinates to real world x,y,z coordinates. Procedure is often called as calibration. Coordinate calibration can also be used to fix image distortions caused by the lens. (Sick AG 2006)

3.4.1 Pattern matching

Pattern matching algorithms check image for predefined patterns. Pattern matching can be very challenging since many different aspects influence how vision systems sees the image. Advanced pattern matching technologies can however identify the object if it's translated, rotated or even covered partially. (Sick AG. 2006)

Successful pattern match results:

- X and Y reference point
- Orientation
- Match score %

(Sick AG 2006)

3.4.2. Blob analysis

Blob analysis classifies pixels into background pixels or blob pixels simply by determining the shading of the pixels (light on dark or dark on light). All connected blob pixels are assigned to the same blob. Everything else is considered as background. Blob finding algorithm reports the number of found blobs and reports their location and area of the each blob. Blob finding has an important role in machine vision, because blob finding can be used to count and measure features with minimal processing load. Blob finding is much less CPU-intensive than geometric model search. (Cognex 2014)

Results of blob analysis:

- Reference coordinate
- Pixel count or surface area of the blob
- Perimeter of the blob area
- Orientation of the blob

(Sick AG, 2006)

3.4.3 Edge detection

Machine vision finds the edges by looking for sharp changes in brightness of the image. Fields where the image sharpness changes considerably are arranged into a line segments. Edges are used to find features and measure dimensions or angles. (Sick AG, 2006)

Edges showing up in image may be caused by:

- Discontinuations in illumination
- Discontinuations in surface boundaries
- Surface markings

3.4.4. Measuring

Machine vision can be used to measure physical characteristics of an object. Physical dimension measured by machine vision can be distance, surface area, diameter, curvature or volume of the object. (Sick AG 2006)

3.4.5. Inspection

In inspection applications machine vision can be used to validate certain features of an object. Vision system looks if specified feature is present or absent. Feature in question can be, for example, a label on the bottle, screws in assembly or defect in a part. (Sick AG 2006)

3.4.6. Bar code and text reading

Machine vision can be used to read codes printed on products or packages to identify the object or contents. (Sick AG, 2006)

Barcode is one-dimensional graphical code, which may contain a short message. Common 1-D code types, machine vision is capable of reading:

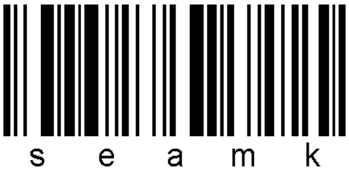


Figure 8: Example of EAN-128 code

- EAN-8 , EAN-13, EAN-128
- Code 39 and Code 128
- UPC-A and UPC-E
- Interleaved 2 of 5

(Sick AG 2006)

Matrix code is a 2-dimensional array, consisting squares or dots. Common machine vision readable matrix codes:

- DataMatrix
- PDF417
- MaxiCode

(Sick AG 2006)

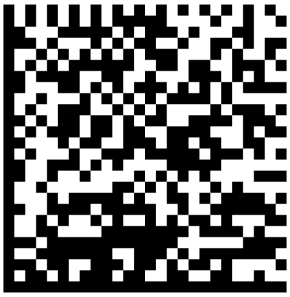


Figure 9: Example of DataMatrix code

Optical Character Verification (OCV) is software tool for checking a printed text. OCV is used, for example, to check if the products have correct date printed on them and that the printed text is readable. OCV compares images to a predefined string. If the string matches, the result is true. (Microscan)

Optical Character Recognition (OCR) is simultaneusly human and machine readable text format. OCR is software algorithm for recognizing unknown text. OCR font type is used when text string must be readable by machine vision. Result of optical character recognition is true or false, depending if reading was successful or not, and a text string, if it was successfully read by the machine. (Microscan)

3.5. Communications

Vision system can acquire information and make decisions based on them but can't take actions itself. Therefore communication between the vision system and other components of automation system is needed. (Sick AG 2006)

Modern machine vision systems commonly use ethernet based communications. Other options are fieldbuses and simple digital I/O.

Results of machine vision may be needed in:

- Programmable logic controllers
- Robots and manipulators
- Databases and production management systems
- Human-machine interfaces

Camera interfaces are used to connect the camera module to a PC-computer or I/O card. Camera interfaces are also often used to supply power for the camera module. (Wilson 2011) Commonly used camera interfaces include Power over Ethernet (PoE), GigE Vision, Firewire and USB. (Ahlroth 2010)

4. INDUSTRIAL PC

When PC-computer is used in industrial automation, the operating system must support real-time execution. Real-time in this context means that the computing operations are executed in a given time frame. Normal operating systems do not support real-time processing, since it is not needed in standard computer applications. Industrial automation also requires fast reaction to hardware signals, otherwise the quickly changing events may be lost. (Barth 2011)

4.1 Beckhoff TwinCAT

Beckhoff TwinCAT automation software solves the problems described above by installing certain extensions to Windows NT kernel. Real-time mode is triggered cyclically by a timer. When real-time mode is triggered, the inputs related to automation tasks are read and an interrupt is used to activate TwinCAT scheduler. Automaton tasks, such as PLC and NC programs are executed while the system is in the real-time mode. After PLC and NC programs finish their cycle, the outputs are updated and computer is switched back to non-real-time mode. Time between real-time cycles is given to Windows operating system. Beckhoff calls this switching between real-time and non-real time mode as double-tick. Figure 10 illustrates functioning of double tick system. Computing time, that real time tasks use can be limited, to ensure the functioning of Windows software. If real-time tasks do not finish in time, the next cycles will be executed in delay. This will be indicated in system flag memory and reactions can be programmed. If CPU supports multiple cores, different tasks, such as PLC runtime, NC runtime and HMI process can be distributed to invidual cores of the CPU. (Barth 2011), (Beckhoff 2012)

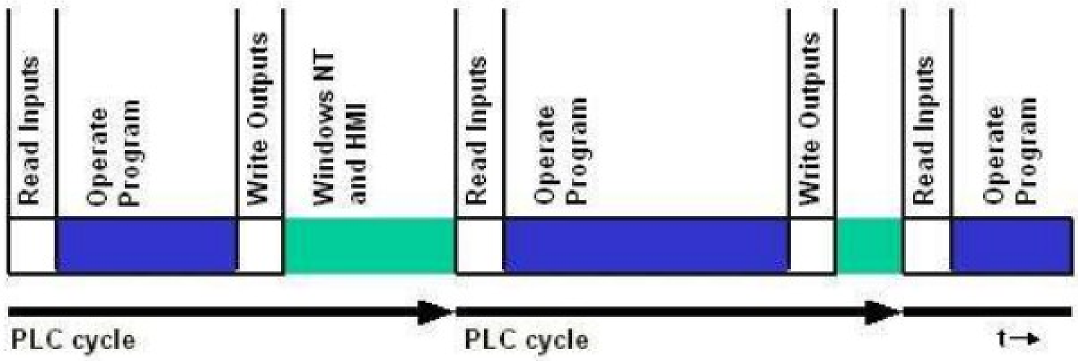


Figure 10: TwinCAT double-tick system

Advantage of the TwinCAT double-tick approach is that Windows operating system and software can be used normally without interrupting real-time processing. TwinCAT software supports virtually any x86 or x86_64 computer running Windows operating system, turning them into PLC or NC controllers. (Barth 2011)

TwinCAT implements ADS router for internal communications between different parts of software system. PLC and NC task operate in real-time kernel mode together with I/O systems. ADS router is handling traffic between the real-time and non-real-time environments. Figure 11 shows structure of TwinCAT ADS router.

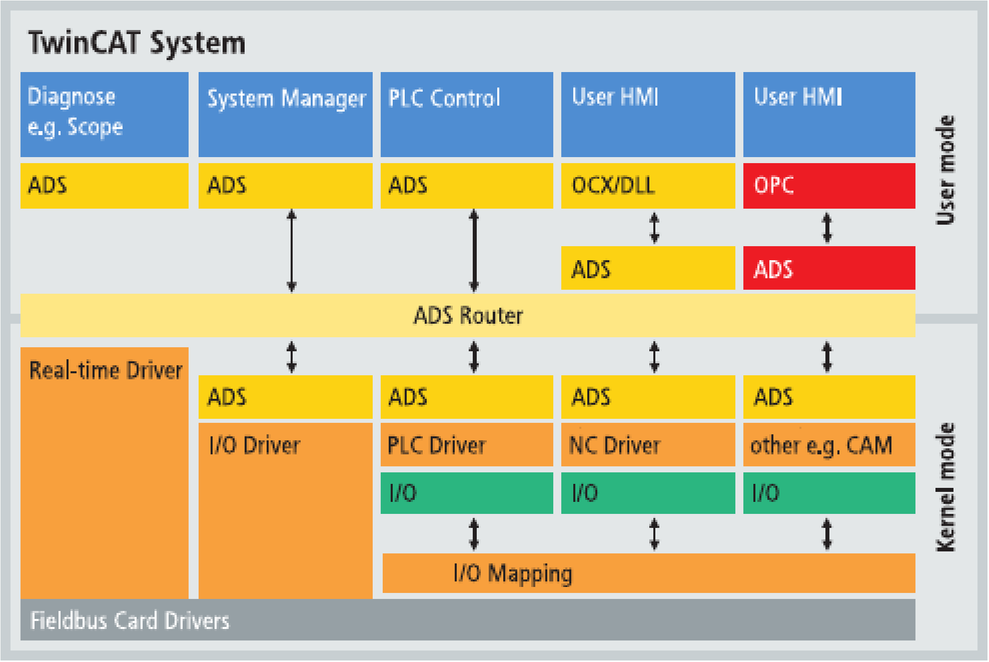


Figure 11: TwinCAT ADS router (Beckhoff)

TwinCAT 3 integrates to Microsoft Visual Studio, which provides a uniform platform for all application development. TwinCAT provides ADS libraries for C#, Visual Basic, C/C++ and Java programming languages. ADS libraries are used for communication between Windows programs and TwinCAT PLC and NC tasks. This feature makes the writing of user interfaces simple. (Beckhoff 2012)

4.2 PLCOpen

Beckhoff TwinCAT follows IEC61131-3 guidelines. (Beckhoff 2014.) IEC61131-3 defines the minimum set of standard programming elements and languages used in automation programming. Standard covers visual programming, such as Ladder (LAD) and function block diagrams (FBD) and written languages, such as structured text (ST) and instruction list (IL). If all automation controllers are programmed similarly, a higher level of code re-usability can be achieved. This makes the coding easier and faster. Standardization of the code also means coders and maintenance personnel require less training to operate the machines. Also upgrading systems to new hardware is cheaper, when the programs are compatible. Goal of the standard is to reduce overall costs of industrial automation. (plcopen.org 2014)

5. INDUSTRIAL ETHERNET

Ethernet is commonly used in homes, offices and in production management level of factories. Industrial communication in the field level sets high requirements for physical and electrical characteristics of the devices. Also delays of ordinary ethernet are insufficient for industrial field level communications. Many different organizations have attempted to create ethernet based industrial communication standards to replace fieldbuses. As a result, there are currently many competing industrial ethernet standards, all of which are incompatible with one another. (Luxemberg Automation 2010)

Industrial ethernet standards:

- Ethernet/IP (ODVA) (note: IP stands for "Industrial protocol" not "internet protocol")
- PROFINET (Profibus user organization)
- Modbus/TCP (Modbus-IDA group)

(Luxemberg Automation 2010)

Using industrial ethernet instead of fieldbus systems is attractive, because ethernet solutions offer much higher data rate than most fieldbuses. Internet protocol offers integration and uniform communication on all network levels, from management to the field level. (Schneider 2013) Ethernet hardware is also commonly available. Combining ethernet and automation networks makes management and diagnostics easier for operating personnel. (PI International 2008)

5.1 PROFINET

PROFINET is one of the best known industrial ethernet standards. PROFINET is based upon a standard ethernet hardware. Ordinary ethernet is commonly used in homes and offices and implements TCP/IP protocol for communication. However, TCP/IP is not suitable for industrial communications due to a relatively long cycle time. PROFINET is compatible with TCP/IP, but in addition offers industrial protocols for real time data transmission. (PI International 2008)

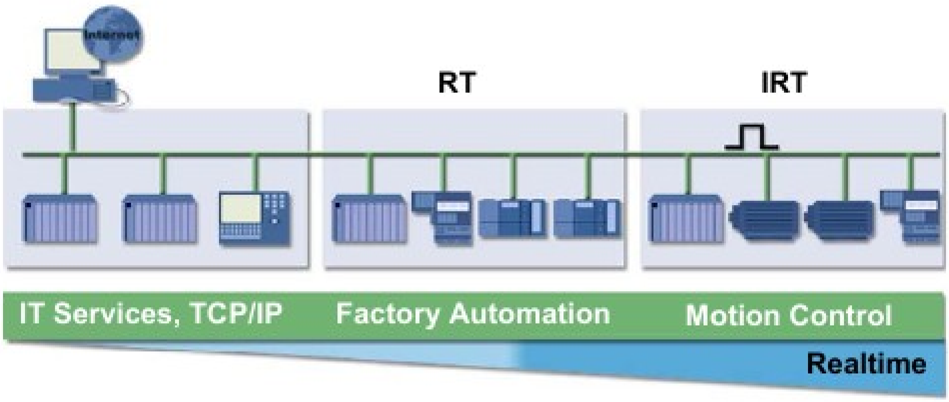


Figure 12: Modular design of PROFINET

Figure 12 shows three different protocols of PROFINET communications:

- TCP/IP protocol is used for non-deterministic transmissions. Performance is equivalent for office world. Cycle time is less than 100ms
- Factory automation level connections use TCP/IP with prioritization (IEEE 802.1Q). Standard messages are sent and received using this priorized TCP/IP protocol. Real time part of the communication uses special automation protocols, which bypass TCP/IP. Compatibility with standard ethernet switches is maintained. Cycle time is less than 10ms
- Isochronous Real Time (IRT) is for time-deterministic connections with maximum real time performance requirements. This kind of connection is required, for example in motion control. In IRT model the ethernet stack is extended in purpose to synchronize all of the communication partners. Special time slot technology, or scheduling is used to reach high level of determinism. PROFINET IRT requires specialized network switches. Cycle time is less than 1ms. (PI International 2008)

One aspect that must be taken into account in industrial ethernets is jitter. Jitter means the variation of delay. In PROFINET IRT networks, jitter is less than, or equal to 1 µs. Too much variation in transmission of cyclic data may shut down the entire automation system. (PI International 2008)

5.1.1. PROFINET GSDML files

Information about basic properties of PROFINET devices, such as communication and diagnostics options are described in GSDML files. Files are provided by device manufacturers. When PROFINET device is added to the PROFINET controller, GSDML file must be loaded into the controller. This way the controller knows how to communicate with the device. GSDML files are written in standard XML format and can be edited with any XML editor complying ISO 15745 standard. (profibus.com)

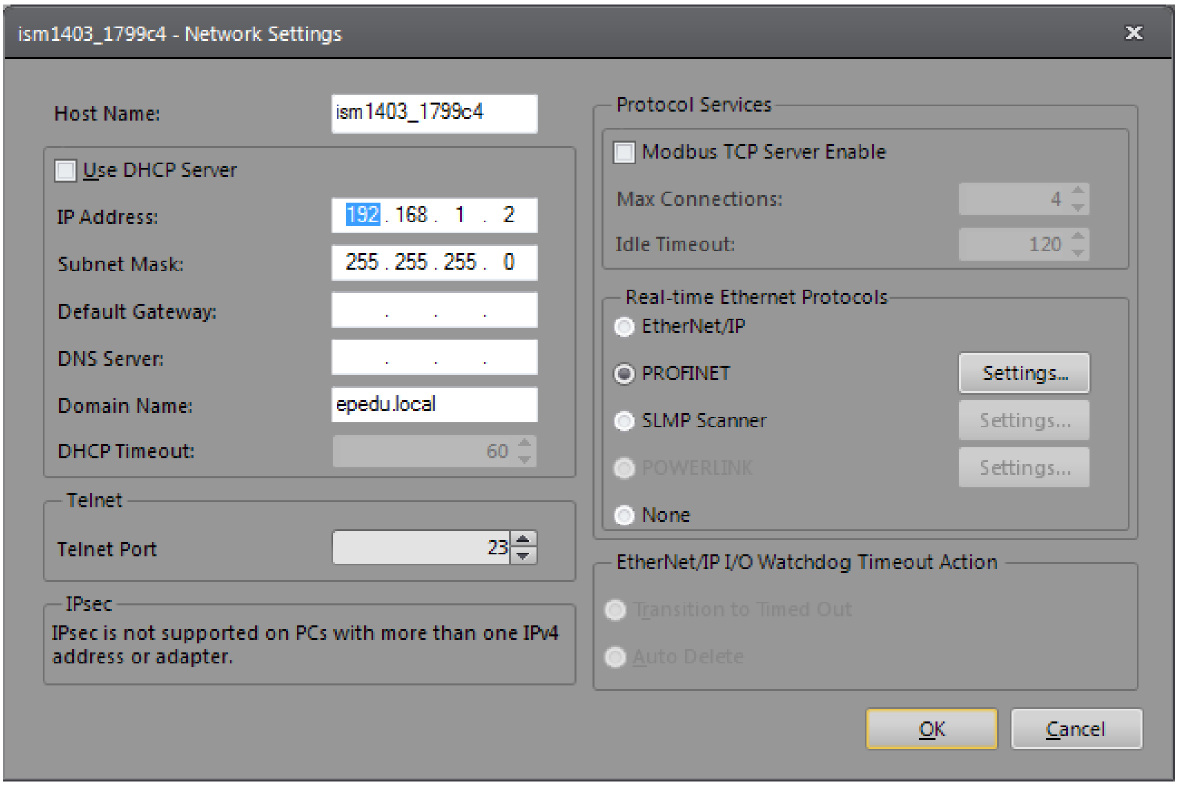
6. IMPLEMENTATION

Cognex In-Sight micro 1403 smartcam was used in this work. The camera has greyscale 1600x1200 sensor and CS lens mount. The camera supports PROFINET, Modbus TCP and EthernetIP industrial protocols. PROFINET was chosen because TwinCAT offers free PROFINET controller supplement.

Cognex In-Sight Explorer programming software is used with Cognex smartcams. In-Sight Explorer quides the user through a few logical steps while creating vision program. In-Sight Explorer has a very simple approach for vision programming and users with only a little experience of vision systems can create basic vision program in few minutes. More advanced user can switch to a spreadsheet mode at any time. The spreadsheet mode gives more control over the software, but also requires more experience.

6.1 PROFINET with Cognex smartcam and TwinCAT

The Cognex smartcam was directly connected to desktop pc running TwinCAT 3. This made possible to try out vision system and PROFINET connection in practice. When connecting smartcam to the PC, very first thing is assigning suitable IP-addresses for the camera and the PC. IP address of 192.168.1.1 and a subnet mask of 255.255.255.0 was set for the PC. IP address of the camera can be assigned using Cognex In-sight explorer software. IP address of 192.168.1.2 was set for the camera. IP configuration of the camera is shown in figure 13. By default the camera uses DHCP, which works fine with In-Sight Explorer software, but caused problems with PROFINET communications. PROFINET controller assigned the camera an address with different network mask as the pc and the In-Sight software was no more able to connect to the camera. It appears that assigning all addresses by hand yields most reliable connection.



ism1403_1799c4 - Network Settings

Host Name: ism1403_1799c4

□ Use DHCP Server

IP Address: 192 . 168 . 1 . 2

Subnet Mask: 255 . 255 . 255 . 0

Default Gateway: . . .

DNS Server: . . .

Domain Name: epedu.local

DHCP Timeout: 60

Telnet

Telnet Port 23

IPsec

IPsec is not supported on PCs with more than one IPv4 address or adapter.

Protocol Services

□ Modbus TCP Server Enable

Max Connections: 4

Idle Timeout: 120

Real-time Ethernet Protocols

○ EtherNet/IP

● PROFINET

○ SLMP Scanner

○ POWERLINK

○ None

EtherNet/IP I/O Watchdog Timeout Action

○ Transition to Timed Out

○ Auto Delete

Figure 13: InSight network settings

PROFINET connection was tested by sending random numbers to the PROFINET network. Random number generator was added to the In-Sight spreadsheet and linked to a PROFINET output buffer. Camera trigger mode was set to continuous to constantly update the output. This was done only to test out the connection.

The next step was to configure TwinCAT for PROFINET master operation. TwinCAT PROFINET controller requires a real-time driver to be installed for the ethernet adapter of the PC. TwinCAT supplies real-time drivers for most (but not all) Intel-based ethernet adapters. The driver can be installed via Windows device manager or directly via TwinCAT network preferences. Initial tests with a certain laptop failed because the driver was not compatible with that specific Intel ethernet adapter. However, a desktop PC with compatible hardware was found and testing was continued. Once the real-time ethernet driver is successfully installed, it is listed in installed and ready to use devices in TwinCAT. Then PROFINET I/O controller can be added to the configuration. Next step is locating correct device from the network and loading device specific GSDML file. This can be done by scanning for PROFINET devices in the network. TwinCAT lists all PROFINET devices found in network.

Vision sensor is selected from the list and GSDML file provided by device manufacturer is loaded to configuration. Before PROFINET controller can be used, a sync task must be created. New sync task with 16 ms cycle time was created and assigned to the PROFINET controller. According to Cognex, too high cycle rate reduces performance of the vision system. Cognex recommends update cycle of 8 ms or 16 ms.

InSight GSDML file defines set of inputs and outputs automatically. These predefined inputs and outputs include set of commonly needed controls, such as trigger control, acquisition count, job control. Random numbers sent by In-Sight vision sensor appeared in inspection results field. Demonstrating that PROFINET connection is functioning.

6.2 Object identification

Working area of vision system measures about 1200x800 millimeters, while camera was mounted at about distance of 1200 mm. Cognex lens advisor was used to choose suitable lens. Based on results of lens advisor, 8 mm wide angle lense was chosen. Aperture of the lense was set to f8, which should produce sharpest possible image. Exposure time was manually set to 14 ms for balanced exposure. Next step is creating new project and calibrating camera to the real world units. Calibration in In-Sight Explorer is actually really simple. Operator can simply select two edges from the image and define real world distance between the edges. After this, all distances measured by the camera are given in real-world units, in inches or millimeters. Triggering mode of the camera was now set to “Network”, because camera will be triggered externally.

Object recognition can be done, for example, by using PatMax algorithm. PatMax is a pattern matching algorithm, which searches images for predefined patterns. User defines location of the object and and area of interest, where object is expected to be. In figure 14 PatMax was trained for searching floppy disks. Pattern matching was successful and floppy disk is highlighted in green. Results of PatMax is location of the object (X,Y), rotation angle, and score of detection.

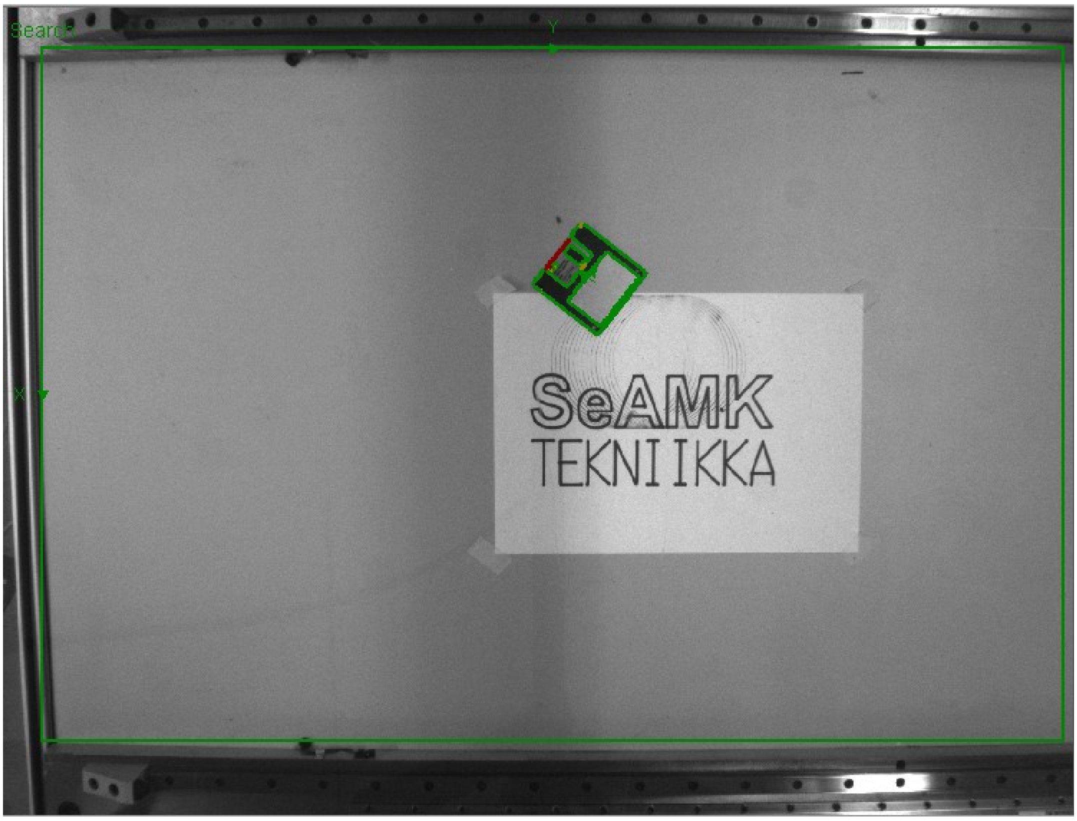
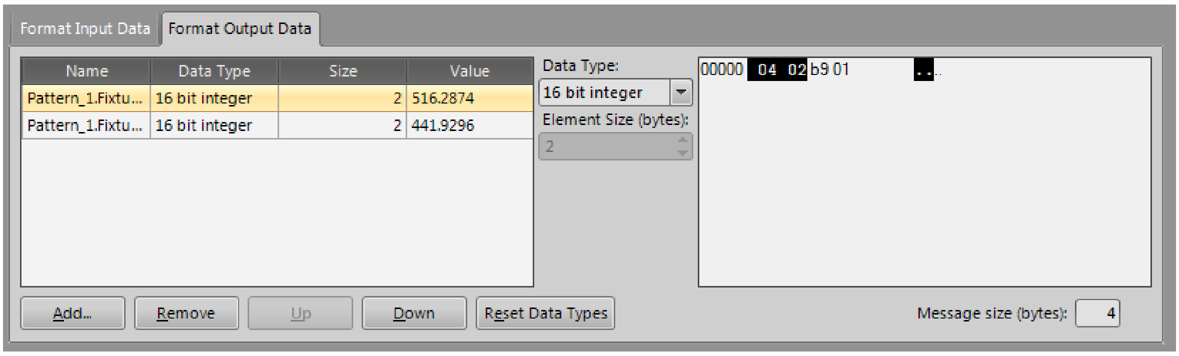


Figure 14: PatMax

After the camera has successfully located the object, results must be exported. Output message sent into PROFINET is basically a sequence of strings, integers or floating point numbers. Receiving end must know structure of the message to make sense of it. Figure 15 shows how the output message was formatted. In this case 16 bit unsigned integer was chosen for both X and Y coordinate of inspection results. First integer is the x-coordinate of the object and second is the y-coordinate.



Name	Data Type	Size	Value
Pattern_1.Fixtu...	16 bit integer	2	516.2874
Pattern_1.Fixtu...	16 bit integer	2	441.9296

Data Type: 16 bit integer

Element Size (bytes): 2

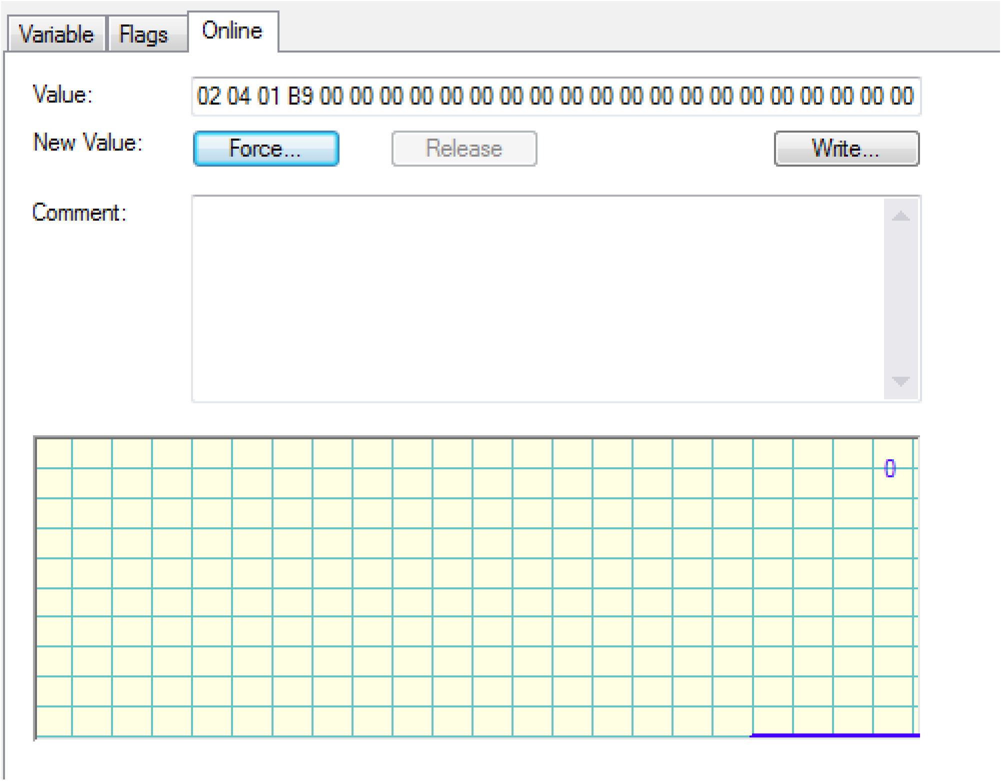
```
00000  04  02 b9 01         ...
```

Message size (bytes): 4

Figure 15: In-Sight output message

6.3 Handling input messages

Figure 16 shows how the message is received by TwinCAT. In this case, first two bytes contain the X-coordinate of detected object, while bytes two and three is the Y-coordinate. Original message consists two 16 bit integers, total of 32 bits. Because TwinCAT reads message as bytes, both integers effectively got split in half. This was bit of a problem since TwinCAT does not allow input message formatting like traditional PLCs. Each byte is saved individually to unique memory addresses and need to be combined back together. Figure 17 shows the basic principle, how the bytes should be handled.



Value: 02 04 01 B9 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

New Value:

Comment:

Figure 16: PROFINET input message shown as hexadecimals in TwinCAT

One solution to combine bytes back to integer is to use bit shift. In TwinCAT, bit shift can be done using SHL block. SHL block shifts the bits left and replaces the right side with zeros. Byte shift is done for the left side of the integer. Right side is then added to the bit shifted left side.

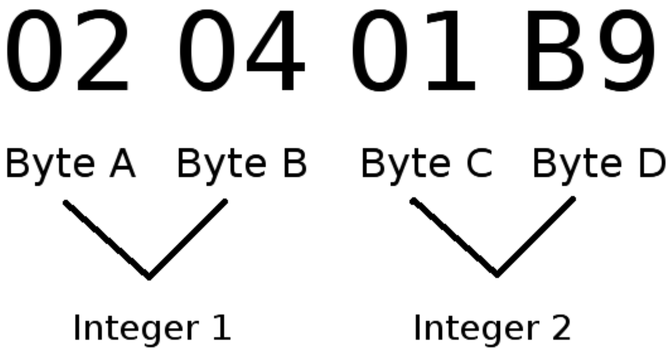


Figure 17: Combining bytes back to integers

Figure 18 shows how bit shift is implemented in TwinCAT PLC task. input_byteA and input_byteB holds the values of X-coordinate of the detected object. input_byteA is shifted left 8 bits using SHL block. Result is stored to unsigned integer intXShifted, containing left side of the input message. The left side is then added together with byteB, containing the right side of integer message. Result is number 16#0204, which is 516 in decimal. This fits to original message shown in figure 15. Y-coordinate is handled similarly, resulting number 16#01B9 or 441 in decimal. This also matches to the original message sent by InSight vision sensor. Bit shifting appears to function as desired.

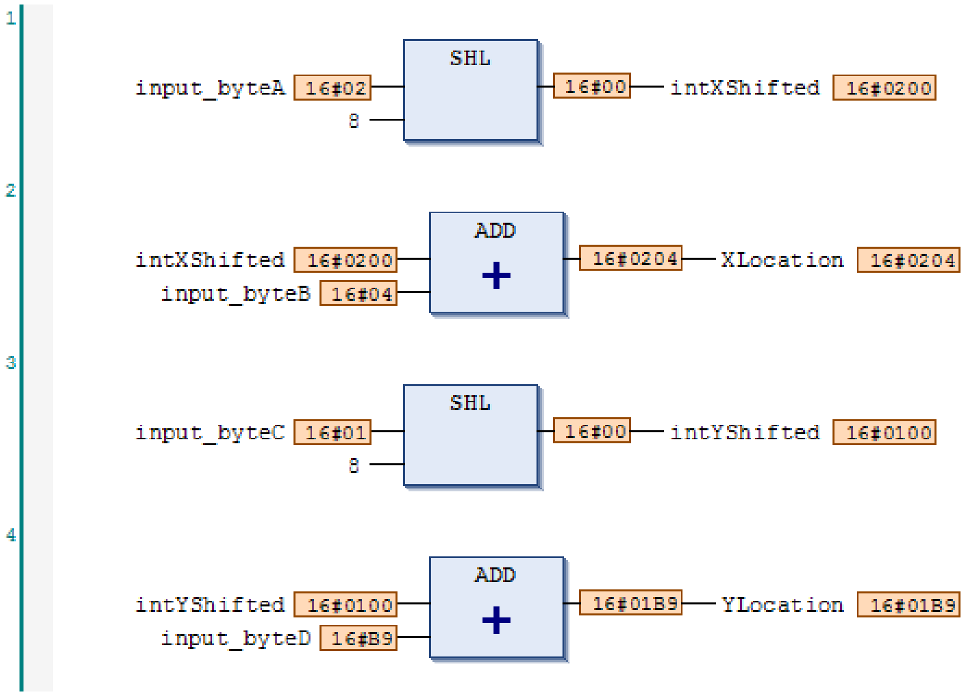


Figure 18: Example of bit shift in TwinCAT

6.4 Point to point movement

Axis control is implemented in TwinCAT NC. TwinCAT NC is capable of doing complex interpolation movements and it can actually execute G-code, similar to NC machines. In this case simple point-to-point movement is sufficient, because more complex movements were not required. For point to point movement, Tc2_MC library needs to be imported to PLC task. This is a standard library and it comes bundled with TwinCAT 3. Blocks mc_power, mc_move_absolute, mc_move_relative and mc_stop are used to control point-to-point movement in PLC task.

Movement control is enabled by using a block called MC_Power in PLC task. A new axis is created by writing a name to the Axis field. Auto declare then creates a new axis_ref variable. This axis variable can be then linked to the NC task and an actual real-world axis. At this point, the PC was not connected to servo drives and the movements were only simulated.

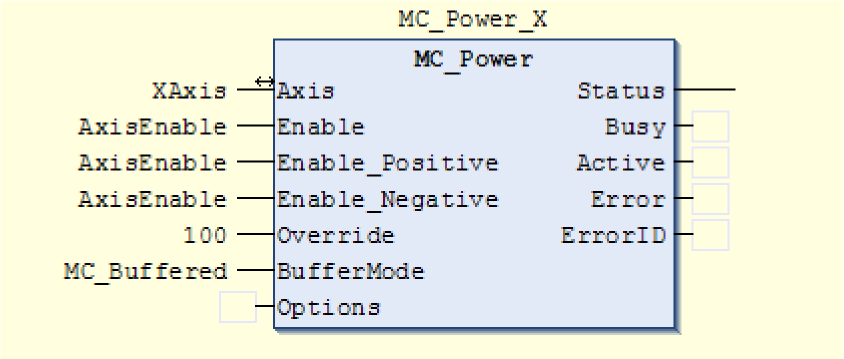


Figure 19: MC_Power

MC_Power, as illustrated in figure 19 enables movement of Xaxis to both directions, when variable AxisEnable is set to true. Override specifies movement speed of the axis in percents. In this case axis is moved at full speed, 100%. This is similar to override setting found in CNC machines. BufferMode specifies how new movement commands are handled if system is still in progress of working previous commands. MC_Buffered mode finishes current movement and then continues to next movement. Options are extra parameters used in rare cases. Options field is in most cases left empty.

To move the axis to a desired position, MC_MoveAbsolute block is used. Example in figure 20 moves Xaxis to a position stored in XCoordinate variable. Velocity, acceleration and deceleration are specified. Jerk means the rate of change in acceleration. Options field is once again left empty. Figure 20 shows how MC_MoveAbsolute was used in TwinCAT. There is also a block called MC_MoveRelative. It is used similarly, but instead of driving axis to absolute position, MC_MoveRelative moves axis with respect to its current position.

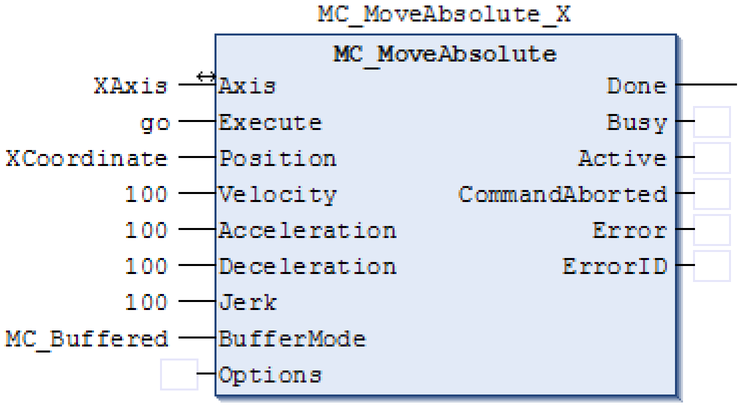


Figure 20: MC_MoveAbsolute

Sometimes movements need to be stopped before reaching target position. This can happen, for example, if user presses emergency stop button. MC_Stop suspends movements of the axis immediately.

Simple sequence was written in TwinCAT to simulate automatic object manipulation. Work cycle of the simulation was following:

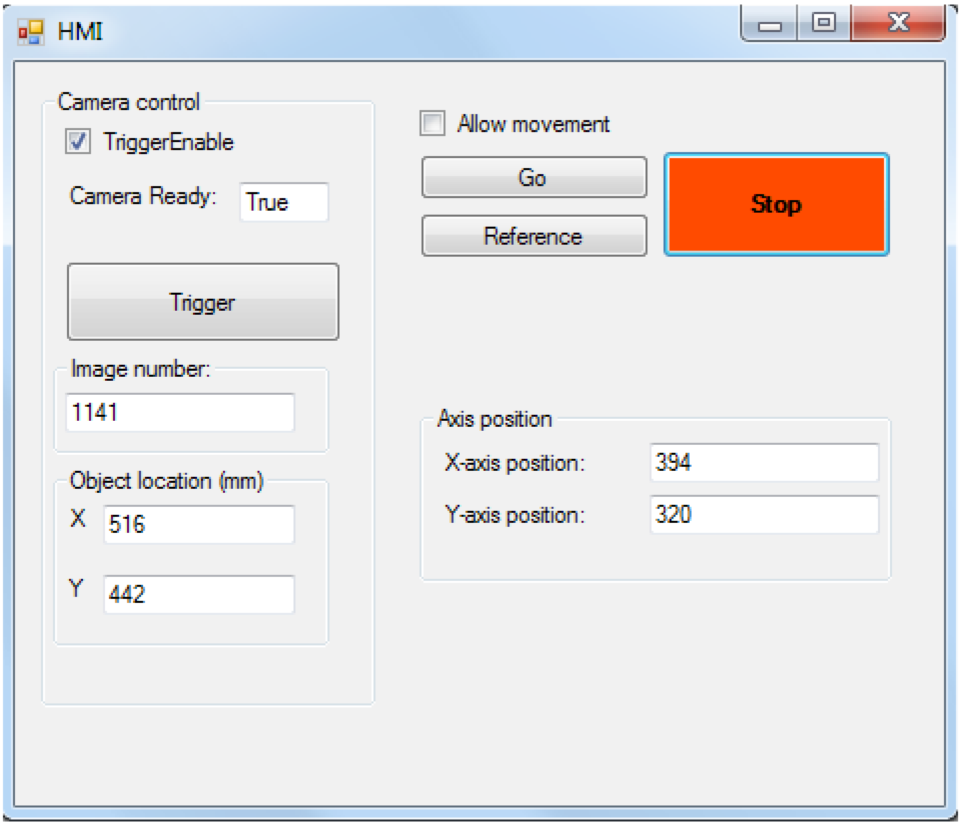
- Trigger enable bit (PROFINET) prepares the camera for taking a picture.
- Trigger bit (PROFINET) triggers the camera
- Job pass (PROFINET) bit indicates the camera has successfully located an object and is done processing.
- X and Y coordinates of the object are read through PROFINET and shown on user interface.
- Movements of the X, Y and Z axis is enabled by using Allow movement button (MC_Power)
- Go button drives X and Y axes simultaneously over the object (MC_MoveAbsolute)
- Z axis goes down, Gripper closes.
- After 1 second delay Z axis goes back up.
- X and Y axes are driven to drop location.
- Z down, gripper open, z up.

- X and Y axes are driven to reference position.
- Pressing Stop button at any time stops all movements immediately. (MC_Stop)

Example of using ADS in C#. This piece of code sets state of PLC variable “start” to true:

6.5 User interface

User interface was written in Visual Studio, using C# language. TwinCAT supplies ADS libraries for C#, which are needed for communication between the C# program and TwinCAT PLC task. By using ADS libraries, C# program can manipulate variables stored in TwinCAT PLC task.



HMI

Camera control

☑ TriggerEnable

Camera Ready: True

Image number: 1141

Object location (mm)

X 516

Y 442

□ Allow movement

Axis position

X-axis position: 394

Y-axis position: 320

Figure 21: User interface

Basic user interface shown in Figure 21 was written for controlling the system. User interface features controls for camera triggering and motion control.

Following example shows how C# program can interact with TwinCAT PLC task.

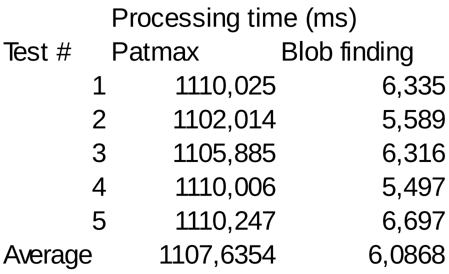
```
using TwinCAT.Ads; //Load ADS library

namespace NetGui

{

    public partial class Form1 : Form

    {

        TcAdsClient myClient; //Create ADS client

        int startHandle; //Create variable handle


       private void Form1_Load(object sender, EventArgs e)

        {

              myClient = new TcAdsClient(); // Create AdsClient

             myClient.Connect(851); // Connect client to local twincat


             //Connect startHandle to variable in PLC task

            startHandle = myClient.CreateVariableHandle("main.start");

       }

    private void startButton_Click(object sender, EventArgs e)

        {

            //Set state of main.start to true

            myClient.WriteAny(startHandle, true);

        }

   }

}
```

TwinCAT.Ads library is imported to the program. New TcAdsClient called myClient is created. MyClient is then connected to local TwinCAT. Default port is 851. StartHandle is pointed to variable main.start, which exists in PLC task of TwinCAT.

By using WriteAny and ReadAny commands, C# program can interact with the variable. In this example, main is the name of the PLC task and start is a variable. Full “address” of the variable is therefore main.start.

6.6 Pattern matching vs blob finding

According to Cognex, blob finding is less cpu intensive and therefore faster than pattern matching algorithms. From perspective of object location both of these tools do the same thing. It seemed like interesting experiment to try out what kind of performance differences there are, if any. Results were indeed very interesting, as can be seen in figure 23.



	Processing time (ms)	
Test #	Patmax	Blob finding
1	1110,025	6,335
2	1102,014	5,589
3	1105,885	6,316
4	1110,006	5,497
5	1110,247	6,697
Average	1107,6354	6,0868

Figure 22: Execution time, Patmax and Blob finding

Blob finding certainly seems to be much faster, finishing around 6 ms, while average execution time of Patmax was about 1,1 seconds. Benchmarking was done by reading execution time indicator in InSight Explorer. Series of five tests was conducted. Position and angle of the object was changed between each test.

7. Results and Reflections

Goal of the project was to connect Cognex smartcam to TwinCAT control system and try out possibilities of vision based motion control.

Initial goal of the project was to connect In-Sight micro 1403 vision sensor to three axis NC manipulator controlled by Beckhoff CX2020 industrial PC. This was not implemented due to time limitations. Instead movements were simulated on ordinary desktop PC.

Most problematic part of the project was combining input bytes back together in TwinCAT. Finding a good solution took a lot of experimenting. Programming the camera itself was quite easy with simple In-Sight Explorer software.

Figure 15 shows image taken on work area with 8mm wide angle lens. Straight lines are curved because of barrel distortion. Barrel distortion is common problem with wide angle lenses. In-Sight Explorer does offer tools for fixing barrel or pincushion distortions and perspective correction.

Experimenting with Patmax and blob finding resulted interesting results. Patmax is more advanced tool and, for example, automatically finds edges from the detected object and therefore makes measuring dimensions of the object easy. This also makes it much slower than blob finding. If advanced features of Patmax are not needed, using blob finding to identify the object makes sense, especially if vision system is used in situation, which requires quick cycle time.

7.1 Future improvements

Original goal of the project was to use machine vision with real NC manipulator. This was not implemented because of few issues. Servo drives of the manipulator require “initialization” when powering up. Otherwise servo controller may show incorrect position at the start. This initialization should be done by moving the axes by a tiniest bit.

Also, the NC manipulator in question, has two servo drives on X axis. Primary axis is controlled directly, but the second axis uses torque sensing to follow the primary axis. This torque sensing should be done in PLC side. Author was unsure how to implement this without risking expensive equipment.

Finally, coordinate system of the vision system and the NC manipulator should be adapted. Origin of the vision system is at the upper left corner of the image. NC manipulator would have totally different coordinates. Adjusting coordinates of the vision system should not be more difficult than simple calculation. Another option would be to give vision system a reference point and measure distance of the object related to that. This reference point could be, for example, a line drawn on the edges work area. This way vision system would also be accurate, if camera moves a little.

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